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# GEOPHYSICS

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## HOW CAN GEOPHYSICISTS BEST SERVE?*

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By this time we should all realize that we are at war—not just our nation or our armed forces but we as individuals are at war. It is only by full realization of this fact that we can hope for a favorable outcome of this struggle for humanity. It behooves each of us, therefore, to consider seriously the question, not am I doing my part, for that allows our efforts to be comparative, but am I doing my best toward the common cause. This is not a question of individual loyalty or patriotism, for loyalty and patriotism must be assumed. Neither is it a question of effort, entirely. It is a question as to how our special experience and training can be most efficient in the war effort.

It is a generally accepted fact that an individual does not have to be in the armed forces of the nation to render his most valuable service in this war. For every soldier, sailor, or marine under arms it takes the work of a number of civilians to supply his needs. Therefore, there should be ample opportunity for everyone to do effective service regardless of age, ability, training or experience. The chief problem is one of organization and distribution so that there shall be a minimum of wasted ability or energy.

We are here as representatives, directly or indirectly, of some few thousand men, technically trained by experience or otherwise for specific jobs in the application of geophysics, chiefly to the discovery of oil. We are now told that our Government greatly needs technical men—physicists, mathematicians, chemists, engineers. Already many men from the geophysical industry have entered war work, either in the armed forces or in special fields, and many of our laboratories and shops are engaged in specific war work of one sort or another. The rest

* Presidential Address, presented at the Annual Meeting, Denver, Colorado, April 22, 1942.

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of us are continually faced with the question as to what we individually should do. It seems to me that before we can answer this question we must first consider two more specific ones: how important is the discovery of oil, and how important are our services in this endeavor.

Let us consider the first of these questions: How important is oil in the war effort? Secretary Ickes, Head of the Office of the Petroleum Coördinator is quoted as saying, in effect, that nothing, without exception, is more important than oil.[1] This may well be true, for this is a war of machines and it is a well recognized fact that oil is essential in the operation of modern machines of war. Not only is it a war of machines. It is largely a war of the air. Improvements and further developments in the art of air fighting rest to a very large degree on the quality of oils that are available for use. Without high grade aviation gasoline and lubricating oils the effectiveness of our modern bombing and fighting planes would be greatly reduced. It is on that added speed, range and load carrying capacity that we must depend for victory. In the same way, oil is essential in the operation of trucks, tanks and naval vessels. A plentiful supply of oil is very essential in all modern warfare, and, without a doubt, those nations which can acquire and retain the oil supplies of the world at the expense of their enemies will win the war.

Granted then that an ample supply of oil is necessary, how essential are new oil discoveries? Largely because of much discussion of proration and allowables, the people of the nation have been led to believe that we have an unlimited supply of oil, and that by simply turning the proper valves, production can be doubled or trebled overnight. What they have not been told, is the fact that such production methods would greatly decrease the ultimate recovery from many fields and that production would suffer a rapid decline. Numerous fields are already showing the effects of just such procedure. Let us review a few of the facts as to the amount of oil that is estimated to be available in the United States.

According to recent figures compiled by the American Petroleum Institute, the estimated reserves in the United States as of January 1, 1942 were 19,586,296,000 barrels.[2] Production for the year 1941 amounted to 1,404,182,000 barrels, at which rate we would seem to have almost a 14-years' supply of oil. However, this does not repreents the facts fairly, because the estimate of reserves is based on an

[1] W. R. Poyd, Jr., Oil and Gas Journal, Vol. 40, No. 26, p. 57, November 6, 1942.
[2] Oil Weekly, Vol. 105, No. 4, p. 46, March 30, 1942.

optimum rate of production, at which rate, production in many fields might stretch out to 25 or more years. If we could look for a decreasing demand for oil, the outlook would be much more favorable. But this is not the case. Instead, since the loss of the very important oil sources in the East Indies, we are now faced with the necessity of furnishing a greater and greater proportion of the oil for our allies. This represents not only a loss of the oil formerly available for use in that area, but in addition the increased amounts required for shipping, since oil, as well as other war materials, must now be transported to the eastern war front. Loss of the Near East supplies would add still another burden on our reserves. It has been estimated by the Office of the Petroleum Coördinator that at least 3,600,000 barrels will be needed daily for military purposes alone in 1942, which is nearly equal to the total average daily production for 1941.[3] Some savings could be made by rationing oil for civilian use, but too great a restriction would undoubtedly have an adverse effect on the production of war materials. It seems certain, therefore, that we may expect a considerable increase rather than a decrease in the oil requirements for the next several years.

Such a demand for oil will unquestionably reduce our reserves in terms of years' supply very materially. No one can say when the war will end and the longer it lasts the greater will be the demand for oil. Certainly we do not wish to be put in the position of trying to render a knockout blow on the last billion barrels of an estimated reserve. Apparently our officials in Washington are taking no such shortsighted viewpoint. In an address before the Division of Production of the American Petroleum Institute in Dallas, Mr. Don R. Knowlton, Director of Production for the Office of the Petroleum Coördinator spoke as follows: "Discoveries and development of new reserves must at least equal consumption. Inasmuch as each new discovery reduces the number of pools remaining to be discovered in the future, the chances for finding new pools are steadily diminishing. . . . This year the industry should drill at least 4000 wildcat wells, preferably 5000, as compared to the 3100 drilled last year. The limited number of wells which will be drilled to develop known fields and new discoveries must be so judiciously placed as to accomplish the development of the maximum quantity of reserves."[4]

It would seem from this statement that the governmental agencies

[3] Don R. Knowlton, Oil and Gas Journal, Vol. 40, No. 43, p. 13, March 5, 1942.

[4] Don R. Knowlton, *loc. cit.*

having to do with the oil supply are convinced of the need for increased reserves and it is on these agencies that we must rely for policy. Although the reserves were increased in 1941 by an amount slightly greater than in 1940, these additions are rather insignificant as compared with the additions in 1937, 1938, and 1939, in spite of the fact that more new fields were discovered in 1941 than in any previous year. This decline in additions to reserves coupled with the ever increasing demand for oil presents a real problem for the oil industry.

We come, therefore, to the second question confronting us: How important are we as geophysicists in this search for new oil fields? The demand for continued exploration at an increasing rate and the need for judicious location of wildcat wells has been pointed out in the remarks of Mr. Knowlton. It is evident that his use of the term exploration has been in its broadest sense, and includes all of those activities which pertain to the discovery of oil from the time an area is looked upon as a prospect until the first well is completed. From this viewpoint, the wildcat driller, regardless of how inadequate his basis for drilling, is as much engaged in exploration as we. Were it not for the fact that the East Texas Field was discovered in just such a venture, we might be inclined to treat this condition more lightly. In this sense, we must realize that we are in competition with all of those agencies which may be involved in the location of wildcat wells. We need, therefore, to look at the record of geophysics in comparison with the other methods of locating wildcat wells to more properly evaluate our activities.

It seems quite unnecessary at this time to go into a lengthy account of the past history of the use of geophysics in the oil business. Most of us are familiar with its beginnings in the early twenties and with its continued development to the present time. However, for our present purpose we do need to look more critically at its record for the past few years in order to predict its effectiveness in the future. For this purpose, the annual reports on Willdcat Drilling by Dr. Lahee in the Bulletin of the American Association of Petroleum Geologists are the best source of information.[5] It is only since 1938 that these reports have covered all parts of the United States and it is to the reports since that time that I desire to call your attention. I am deeply indebted to Dr. Lahee for permission to use a portion of the results of his analysis for 1941.[6]

[5] Frederick H. Lahee, Bull. Amer. Assoc. Petrol. Geol., Vol. 23, No. 6, pp. 789–794, June, 1939; Vol. 24, No. 6, pp. 953–958, June, 1940; Vol. 25, No. 6, pp. 997–1003, June, 1941.

[6] Private communication.

TABLE I

COMPARATIVE RECORD OF METHODS OF LOCATING WILDCAT WELLS

| | | *Geology* | | *Geophysics* | | *Geology-Geophysics* | | *Sundry Non-technical* | | *Unknown* | | *Totals* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *Dry* | *Prod.* | *Dry* | *Prod.* | *Dry* | *Prod.* | *Dry* | *Prod.* | *Dry* | *Prod.* | *Dry* | *Prod.* |
| 1938 | Totals | 1041 | 192 | 252 | 78 | 69 | 31 | 535 | 44 | 372 | 24 | 2269 | 369 |
| | Ratios | 5.4 | 1 | 3.2 | 1 | 2.0 | 1 | 12.2 | 1 | 15.5 | 1 | 6.1 | 1 |
| 1939 | Totals | 1006 | 135 | 400 | 69 | 40 | 13 | 666 | 43 | 207 | 10 | 2319 | 270 |
| | Ratios | 7.5 | 1 | 5.7 | 1 | 3.0 | 1 | 15.0 | 1 | 20.7 | 1 | 8.6 | 1 |
| 1940 | Totals | 1204 | 198 | 446 | 100 | 81 | 22 | 797 | 35 | 144 | 11 | 2672 | 366 |
| | Ratios | 6.0 | 1 | 4.5 | 1 | 3.7 | 1 | 23.0 | 1 | 13.0 | 1 | 7.3 | 1 |
| 1941 | Totals | 1380 | 300 | 437 | 143 | 111 | 28 | 771 | 30 | 62 | 2 | 2761 | 503 |
| | Ratios | 4.6 | 1 | 3.1 | 1 | 4.0 | 1 | 25.9 | 1 | 31.0 | 1 | 5.5 | 1 |
| | TOTALS | 4631 | 825 | 1535 | 390 | 301 | 94 | 2769 | 152 | 785 | 47 | 10021 | 1508 |
| | RATIOS | 5.6 | 1 | 3.9 | 1 | 3.2 | 1 | 18.3 | 1 | 16.7 | 1 | 6.6 | 1 |

TABLE II

COMPARISON OF TECHNICAL AND NON-TECHNICAL METHODS

| | | | | *Technical* | | | | *Non-technical* | | | | *Totals* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | *Dry* | *Prod.* | | | *Dry* | *Prod.* | | | *Tech.* | *Non-tech.* |
| 1938 | Totals | | | 1362 | 301 | | | 907 | 68 | | | 1663 | 975 |
| | Ratios | | | 4.5 | 1 | | | 13.3 | 1 | | | 1.7 | 1 |
| 1939 | Totals | | | 1446 | 217 | | | 873 | 53 | | | 1663 | 926 |
| | Ratios | | | 6.6 | 1 | | | 16.5 | 1 | | | 1.8 | 1 |
| 1940 | Totals | | | 1731 | 320 | | | 941 | 46 | | | 2051 | 987 |
| | Ratios | | | 5.4 | 1 | | | 20.5 | 1 | | | 2.1 | 1 |
| 1941 | Totals | | | 1928 | 471 | | | 833 | 32 | | | 2399 | 871 |
| | Ratios | | | 4.1 | 1 | | | 26.2 | 1 | | | 2.8 | 1 |
| | TOTALS | | | 6467 | 1309 | | | 3554 | 199 | | | 7776 | 3753 |
| | RATIOS | | | 4.9 | 1 | | | 17.9 | 1 | | | 2.1 | 1 |

In these analyses, the wildcats are listed by states as dry or producing under the five headings of geology, geophysics, geology and geophysics, sundry non-technical, and unknown. These figures vary greatly from state to state and would seem to deserve careful detailed study as indicating in what areas the different methods are most effective. For our present purposes, however, we are more interested in the comparative results of the different methods for the country as a whole rather than for particular areas. Table I has been compiled from these data to show a comparison for the separate years and also to show the average relative effectiveness for the four years. It will be noted that geophysics ranks somewhat above geology in effectiveness and both are well above the record for the non-technical locations. Of particular interest is the fact that the partnership of geology and geophysics, on the average, and also for the separate years with the exception of 1941, shows the best record. This appears to me to be a good sign, for it indicates a willingness on the part of geologists and geophysicists to coöperate more fully. As time goes on I should expect more and more of the wells to be placed in this column for it should become increasingly difficult to divide the credit or responsibility for locations. For this reason, in Table II, the geological and geophysical locations have been grouped as technical, and the sundry non-technical and unknown locations as non-technical. The average ratios in this case are 4.9 to 1 for the technical and 17.9 to 1 for the non-technical, or a relative effectiveness on the average for the four years of more than 3.5 to 1 in favor of the technical. For 1941 this ratio is more than 6 to 1. The last column shows a comparison of the number of locations made on technical and non-technical advice which indicates a gradual increase in the proportion of locations on technical advice.

Let us engage in a little speculation as to what the result might have been had all the wildcat wells been drilled on technical advice. Probably many of the locations would not have been drilled and possibly some of the producers would have been missed, but let us suppose that other locations would have been found to make up the total number. In the four years 3759 wildcat wells were drilled on non-technical advice, of which 199 were producers and 3560 were dry holes, or 1 in 17.9 was a producer on the average. Suppose these wells had been drilled on technical advice with the average success for the four years. On the average, 1 well in 4.9 would have been a producer from which we should expect 767 producing wells or an increase of 568 new fields for the four years, an increase of more than one third.

This record of geophysics is far from perfect but from the above analysis it is quite evident that the combined forces of geology and geophysics are far ahead of random drilling in effectiveness in finding new fields. With the exception of one year, there has been a continual increase in the number of new fields discovered for at least six years. However, the fields are becoming smaller on the average and the additions to the reserves are not impressive. But this cannot be construed as a decline in effectiveness in finding new fields, for certainly it is more difficult to detect small structures than large ones. It is possible, of course, that these figures do not represent the true state of affairs today, for the discoveries of 1941 represent in some cases, at least, structures found in previous years. We have no way of evaluating the present effectiveness except in light of past performance. If fewer structures are now being found, it is all the more advisable that we redouble our exploratory efforts, developing new methods and pursuing the old ones more assiduously.

It is admitted that more effective means of locating stratigraphic accumulations are needed. For this purpose geochemical and the more recent fluorographic methods have considerable appeal. However, the lack of outstanding successes have prevented their widespread acceptance. Recent developments in the electrical field have revived this method to some extent but more specific information is not available. In regard to the older methods, I feel qualified to speak only of the seismograph and I would like to suggest three ways in which this type of exploration can best be pursued.

Of all the proved methods the reflection seismograph offers the greatest opportunity for benefit from detailed study and this is one direction in which effort should be made. This may take the form of greater density of control such as is being used in parts of Oklahoma and Kansas or in more detailed study of fault problems in the Wilcox trend or in the Gulf Coast of Texas and Louisiana. It is also being used with considerable success in detailing known structures in the Gulf Coast especially as to fault patterns and as to the variation of structure with depth. Of all methods, the seismograph alone serves as a tool for vertical as well as horizontal exploration. This is proving to be especially valuable in California and in parts of the Gulf Coast.

For this detailed type of work to be of the greatest possible value, the prospects should be carefully chosen, and for this reason close coöperation between the subsurface geologist and the geophysicist is very important. Many of the prospects will come from subsurface

information, and failure of the seismograph to check well information may indicate faulting or changes in sedimentation with resulting changes in velocity. These possibilities must be carefully considered and evaluated. Other prospects may come from gravity, magnetic or geochemical anomalies as well as from a re-evaluation of old seismic data. Reasons for failure to confirm these anomalies should be searched for, by both the geologist and the geophysicist.

A second field for seismograph work lies in those areas not now believed to be of economic interest but where good reflection work can be done cheaply. It has not been many years since the Wilcox trend of Texas and Louisiana was in this category. Other areas which are overlooked at the present time may prove equally important.

There is a third field for the seismograph, best illustrated by parts of West Texas where the results have not been very satisfactory. Continued research in instruments and methods should be maintained in these areas, at least until a more satisfactory exploratory tool is devised.

Let us return now to the original question: How can we render the most effective service to our country? It would seem that any reduction of geophysical activity or any reduction of its efficiency cannot well be permitted at this time. Already many men have been called into service and it is becoming increasingly difficult to find capable men for training as replacements. The only conclusion that can be drawn, therefore, is that we should not, for patriotic reasons alone, make a mass migration into what may be called more specific war work. We represent a rather small group, and there is a minimum of personnel beyond which efficient work cannot be done at its present level. If we are particularly fitted for some specific task in the war effort and our present tasks can be taken over by others, undoubtedly we should offer our services. If we remain in geophysics, every effort should be made to increase the effectiveness of our methods of oil finding and to search for new methods. Until some more effective method of finding stratigraphic trap fields is discovered, surely we must continue to pursue the structural type with more vigor and determination. In any case, we should make sure that our specialized training is used to its fullest capacity wherever we serve.

# SYMPOSIUM—APPLICATION OF GEOLOGY AND GEOPHYSICS TO WAR AND POST-WAR PROBLEMS OF THE PETROLEUM INDUSTRY*

## GEOPHYSICS ON THE PACIFIC COAST

HENRY SALVATORI†

In recent years practically all operators in California have largely confined their geophysical work to the reflection seismograph method. There has been a relatively small amount of gravity, magnetic and geochemical work, but with some minor exceptions the reflection method has been and still continues to represent by far the major geophysical method of exploration utilized in this area. But for one doubtful exception, all geophysical discoveries in recent years can be attributed to this method of exploration.

In view of the decline in the discovery of new oil reserves and the strategic position of California to the war effort, it is essential that we examine the steps and direction of the near-future exploratory effort. It has been pointed out in a companion discussion that 300 million barrels per year of new oil must be discovered in California in order to meet the demand. During the past three years an average of only 40 million barrels per year have been discovered. It is apparent, therefore, that our past efforts have been far from successful. It has also been stated that the declining discovery rate since 1939 suggests that the reflection method as it has been employed has served its period of maximum usefulness, and must soon be supplemented or replaced by a new idea or method.

While I fully concur in the desirability of evolving a more effective method of exploration, at the present time it appears that no such method is in sight and that we are confronted with the necessity of doing more with the methods we already have. Undoubtedly, the cost will be greater, but I see no reason for believing that the discovery rate will not be materially increased if sufficient effort and expenditure is made available for this purpose.

* The papers published herein constitute the geophysical contributions to the discussion at a joint session of the American Association of Petroleum Geologists, Society of Economic Paleontologists and Mineralogists, and Society of Exploration Geophysicists, at the Annual Meeting, Denver, Colorado, April 22, 1942.

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While the total oil discovered has declined since 1939, the total number of new fields has generally maintained its previous level. Actually, in 1941, the number of dry holes per field discovered reached a minimum figure as compared to former years. This would seem to indicate that the effectiveness of the present attack in discovering new fields has not diminished. The fact that the productivity of the new fields has been small can be attributed chiefly to the thinness and low quality of the oil sands encountered and not entirely to the size of the structural features. The past discovery record in California justifies the belief that extensive use of the present effective seismograph and geological methods will uncover occasional fields of much greater value than those discovered in 1941.

In recent months most of the California seismograph work has been directed towards the careful delineation of structural anomalies and unconformities with a view of discovering stratigraphic traps and other more complex types of reservoirs. The first seismograph work in California was performed with the chief aim of discovering very large anticlinal structures. This required loosely spaced shot points and a minimum of detail. At the time, it was generally thought that any structure with less than 500 or 600 feet of closure merited little interest. Later, when most of the principal areas had been loosely explored, smaller but still good-size structures received attention. In recent years, the smallest closed structure capable of being mapped became of interest and now that the chances of discovering closed structures have greatly diminished, all types of structural anomalies are carefully explored and studied.

This type of work requires the close and coördinated effort of both the geophysicist and the geologist, and predictions can be made with much less assurance. Nevertheless, by employing proper techniques and high density of observation points, gently dipping structural features can be delineated and the convergences and unconformities of the beds detected. With this information and other available geological and subsurface data the geologist can indicate possible oil producing areas. Perhaps more dry holes will result than in the past, but by the continuation and extension of our present methods of attack there are good reasons for feeling confident that oil will be discovered in California in sufficient quantities to meet at least the very essential demands.

It might be argued, and this is open to question, that a similar amount of oil might be discovered in other oil provinces with more cer-

tainty and at less cost. The answer to this is simply that oil is needed in California and even with a higher discovery cost it is cheaper to find it locally than to discover it elsewhere and transport it to California. Moreover, with the lack of transportation facilities, oil must be available from California fields in order to meet the demands of the war effort on the Pacific Coast.

## GEOPHYSICS IN THE PERMIAN BASIN

JOHN H. WILSON†

The application of geophysics in the Permian Basin to war and post-war problems is largely one of location of new oil reserves. Given governmental approval, allocation of essential supplies and adequate financial incentive, which involves such factors as price, allowables, outlets, etc., geophysical work may be expected to continue in fair volume during the war because the Permian Basin still contains many highly prospective areas not yet satisfactorily explored by geophysical methods.

The Permian Basin generally involves the greatest expense per unit covered of any dry land area. In addition, land owners have come to consider geophysical permit fees as a source of income, subject to arbitrary increases. Most University lands have been withdrawn from geophysical exploration. These factors are hampering logical regional exploration campaigns and many companies have curtailed their geophysical work; others may do so.

The past few years have seen many improvements in seismic procedure and equipment. However, in many areas record quality still is so poor that seismic indications of structure can be considered only as anomalies rather than structural mapping. Each year the seismograph enlarges the area to which it can be successfully applied. Progress is being made in the Basin's greatest problem, that of working the Edwards Plateau and other areas covered by formations which adversely affect the record quality. This has come about by better understanding of the factors involved, by changes in field procedure, such as location of shot holes and geophones in relation to surface and geological conditions, and by changes in instrument design, such as more flexible control of volume, frequency and other instrumental char-

† Independent Exploration Company, Houston, Texas.

acteristics. Increasing accuracy of results in all areas can be hoped for by improvements of technique, by a closer correlation of geological information, and by a better understanding of the nature and degree of velocity changes through more velocity surveys. A moderate revival of refraction surveys with some improvement in technique has been noted. Much thought is being given to stratigraphic types of oil fields and a study of intervals between correlatable reflections has already given valuable information on convergences and unconformities and may be increasingly important in deep exploration. Sharp changes of dip on flanks of structure where the largest wells are often encountered, such as on the flank of the Foster Pool in Ector County, Texas, have been successfully located in advance of drilling.

Regional coverage of the Basin by gravity meter surveys is being made by a number of companies and will be completed in the next few years. Isogam maps from gravity meter surveys are superior to those from torsion balance in areas of extremely rapid and local variations in gradient. Due to more rapid and cheaper coverage gravity meters have largely supplanted the torsion balance for regional work, although some companies still prefer the torsion balance for detail of local areas. With regional coverage for a background, there is developing a better understanding of the nature and significance of gravity anomalies. Regional corrections and residual gravity studies will be increasingly important.

The Basin has been more or less completely covered by magnetic surveys in the past. There has been a moderate revival of magnetic methods, for although the data are far from satisfactory in most areas as an indication of local structure, they certainly have value as a background for other geological and geophysical activities.

Soil analysis surveys are being made, but information is lacking for evaluation of the future utility of the method in the Permian Basin.

Electrical prospecting is being tried, but most of the present activity is with newer types of equipment on which there is little public information on the technique or results.

It is believed that the prerequisites for successful prosecution of geophysical exploration and development of new reserves in the Permian Basin are financial incentive, necessary supplies, continued improvement in procedure and equipment, regional coverage, multiple geophysical methods, closer correlation between geology and geophysics, and some amelioration of the permit situation.

# GEOPHYSICS IN THE MID-CONTINENT

L. Y. FAUST†

Exploration of oil, before the advent of scientific methods, was based on the principle: "Oil is where you find it." The high concentration of geophysical crews in old producing areas suggests we may now be operating on the principle: "Oil is where you *FOUND* it."

This very intensive work, restricted to the most prolific regions, results in much duplication of effort. These areas can probably yield little more than the bread and butter type of field, which add little to the known reserves until a new method or a new geological conception is developed.

There are many provinces wherein exploration has been held to a minimum. Many have been considered unattractive because the very sketchy geological control available suggests that the section is unfavorable, or that structure is lacking.

Occasionally those places once considered unattractive contribute an important discovery. Examples are Fitts, Tinsley, Ten Sections, Shuler and more recently the Midway pool of Arkansas. The last two mentioned illustrate a too frequent type of exploration. Following the discovery of Rodessa, geophysical crews descended upon Southern Arkansas in sufficient numbers to represent practically every major company. When the play cooled they departed. The Shuler field was brought in and immediately a new intensive seismograph survey began. This area was intensively shot and re-shot up to a certain line. North of this line very little work was attempted for the section was considered unfavorable. Again the crews were removed from this area. Eventually the Midway Pool was opened north of the line where the section was supposedly unfavorable. The seismograph crews have returned!

A more orderly exploration of all areas not thoroughly condemned as potential oil territory should result in better attainment of the reserves now necessary for the war effort. The size of these unexplored provinces should result in less duplication of shooting, and more coverage per crew.

The selection of prospects in this category will be governed partly by transportation considerations, and nearness to the points where

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the oil is needed. However, in the absence of a definite geological lead, the quality of the geophysical information would afford an excellent criterion for determining the areas to be worked first.

Whenever a recognized geophysical method can be applied, the best procedure certainly arises from the cooperation of geologists and geophysicists. Both must be heard if the correct solution to any geophysical problem is to be found. This is especially necessary if geophysics is to be successfully applied to the problem of the stratigraphic trap. If this is to be solved by present methods, it can only be by the closest liaison between geologist and geophysicist—each contributing those facts which he knows to be true and each admitting the exact amount of guessing that has gone into his solution.

The Mid-Continent has been the scene of the most effective use of geophysical methods, particularly the reflection seismograph. Although these provinces are remote from the seaboard and hence from the centers of the need for oil, there are other factors which emphasize the importance of this region.

In Lahee's "Wildcat Drilling in 1940," and his recent report for 1941,[1] he tabulates for each state the number of discoveries and dry holes credited to each method of exploration. There is reason to doubt whether there are many wells drilled on geophysics alone without vital geologic assistance. There is also probably a minor portion of the wells credited to geology which were not at least checked by geophysics prior to drilling. Accordingly, it seems best to combine the score of geology and geophysics to obtain the best comparison between states. These figures averaged for 1940 and 1941 show the following order of success:

| *State* | *Ratio Dry Holes to Producers* |
|---|---|
| Oklahoma | 2.4 |
| Arkansas | 3.3 |
| Kansas | 3.6 |
| Louisiana | 3.9 |
| Illinois | 4.4 |
| Texas | 5.2 |
| California | 7.0 |

The three states with the best record are in the Mid-Continent. On the basis of this evidence of recent past performance the Mid-

[1] Lahee, Bull. Amer. Assoc. Petrol. Geol., Vol. 25, No. 6, pp. 997–1003, June, 1941; Vol 26, No. 6, pp. 969–982, June, 1942.

Continent looks very attractive. Unfortunately, most of these discoveries are small fields sandwiched in between older pools. Thus, in spite of the excellent record for Oklahoma, we have the decline in production demonstrated by statistics.

While there are good possibilities of finding more fields in areas of good shooting, particularly in Central Oklahoma, these will in general be of small extent.

The problem in Oklahoma used to be one of mapping Viola structure rather than Hunton or Mississippian. More recently, the Hunton has come in for a greater share of interest and this previously unwanted reflection is finally having its day.

Western Oklahoma has received relatively small attention—chiefly due to the nature of the section and the rather poor quality of the reflections. Certainly, some improvement in technique is necessary in order to shoot this region accurately and cheaply.

Kansas presents the same problems as Oklahoma with the addition of many new ones. While reflections are obtained without too much difficulty, very careful and concentrated work is necessary for their correct interpretation.

The territory offering possibilities for widespread geophysical activity in the Mid-Continent lies to the north in Nebraska and the Dakotas. Here are large regions where good quality reflections can be obtained and where major oil fields may possibly exist.

## GEOPHYSICS IN CANADA—ABSTRACT

L. I. FREEMAN†

Geophysical methods applied to oil exploration have been used in Canada shortly after their introduction in the United States. Apparently the brevity of each survey by any method precluded any particular success. Unfortunately their first application was to areas in which no great success has been attained since. Within the past five years, however, due to the introduction of the gravity meter and the improvement in reflection seismograph methods and instruments, Canada is well along in its exploration with geophysics.

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Geophysical methods, chiefly the reflection seismograph, but some gravity meter work, are being used from the "foothills" area in Western Alberta, through the plains of Alberta and Saskatchewan and as far east as Prince Edward Island. By far, most of the work is being done in the "plains" area of Alberta and Western Saskatchewan. This area of gentle dips in Cretaceous and Paleozoic rocks offers abundant reflection data. Glacial drift, while no particular handicap, calls for attention to near surface velocity differences as well as requiring deep shot-holes in some areas. The character of seismic records in the "plains" area can be compared to the North Texas area, such as Montague, Clay and Archer Counties. Good correlation work can be done.

The "foot-hills" area, including Turner Valley and other localities close to the mountains, is a more difficult area for shooting. The surface drift becomes coarser, and surface formations harder for shot-hole drilling. Where the dip is not excessive and thrust-faulting not present, correlation work can be done. Where dips become great and thrust-faulting is present, continuous profiling or other method of dip work must be done. The latter becomes an expensive method at times due to rough topography, large charges of dynamite, and the small percentage of usable records secured. Records here compare in quality with those from the sharply folded areas of Southern Oklahoma.

Because of the prolific production of oil and gas at Turner Valley, exploration will no doubt continue in the "foot-hills" area in search of similar structures, although the cost per acre is high. To date, oil or gas fields located by the seismograph in the "plains" area, while not as prolific as desired, seem to be present in quantity, judging from exploration plays. The area of possible "plains" structures is large and will probably see a large number of field crews active during 1942. During 1941 no less than six major operating companies from the United States had nine seismograph crews in Alberta and Saskatchewan and three gravity meter crews. One seismograph crew worked in Prince Edward Island. The work in 1941 represented a large increase in field activity over 1940. As long as the World War continues to confine oil exploration to this hemisphere, undoubtedly Canada will see an even greater increase in field work with geophysical methods.

# CONTRIBUTION OF GEOPHYSICS TO THE NATIONAL EFFORT*

HERBERT HOOVER, JR.†

In the present emergency of the war, applied geophysics faces many complex responsibilities. I believe that these responsibilities can be divided into two groups:

First—we must do everything possible to increase our petroleum reserves. I would like to delay my comments on that subject until the latter part of my paper.

Second—we have the obligation to make available our experience and resources, wherever they may be most needed, on problems that have arisen outside the petroleum industry.

This is a technical war and it must be won by technical men, using technical devices. Dr. Heiland has outlined, in an excellent publication of the Colorado School of Mines,[1] some of the methods and devices that are being used in modern warfare. Others such as the protection of ships against magnetic mines by de-gaussing, and the location of airplanes by the reflection of radio waves, have found their way into the press. There are many more that must remain secret, but which challenge the imagination to an even greater degree. All of them, however, are right up the alley of the geophysicist. In fact, geophysicists are rated by many to be among the most valuable technical personnel available. As a result of their training and experience, they are especially adapted to the development, design and operation of many of the devices necessary in this important branch of the war effort. Many of the familiar faces that are missing from this meeting are of men engaged in various aspects of this work at present, and their technical contributions have already been tremendous.

Some of the geophysical research and development organizations have also been engaged in this type of work, as complete, integrated units, and are making a considerable contribution to the national

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† President, United Geophysical Company, Pasadena, California.

[1] Geophysics in War. Quarterly Journal of the Colorado School of Mines, Vol. 37, No. 1, January, 1942.

effort. By so doing they are accomplishing two things. First—they are providing smoothly-running organizations in which the collective ability of the group far exceeds that of any single individual. Second—all of the facilities for research and construction already exist.

It is certain, in view of the extreme scarcity of qualified personnel, that men who are not already engaged in this type of work will be gradually called into the government services. It seems imperative, therefore, that those organizations which have not already done so should go after war work immediately. There are at least three good reasons I can think of. First, it is very definitely an obligation toward the war program. Second, their organizations will still be available to meet geophysical problems as they arise, and third, much of the experience and technique thus gained is indirectly of great value in exploration.

Perhaps I can give a few examples from some of our own experiences. My own company has been engaged in such work for over a year, during which time we have had to expand this branch of our personnel and facilities by more than 500%. We soon found that we had to go out and scrap for every bit of work that we obtained. Nobody came around and asked us to do anything—except to lend them personnel—permanently.

We also came to the conclusion, contrary to the newspaper reports, that there was no profit in it. We realize, however, that we will have an excellent organization and a lot of very valuable experience when it is all over. Furthermore, our direct contact with the Army, Navy and Air Corps has driven home to all our personnel the seriousness of the conflict we are engaged in.

One line of work that I am able to disclose may be of interest to some of the seismologists present. It involved the development and construction of equipment for measuring and analyzing static and dynamic strains, vibration and flutter in high speed airplanes.

As the speed of airplanes begins to approach the speed of sound, many complex aerodynamic problems arise. One of the most serious of these is flutter, or sustained oscillation. These vibrations may build up to such large amplitudes that a portion of the structure, such as an entire wing or tail, may break off. During experimental work on such problems, seismometers or electrical strain gauges are fastened to various parts of the structure. During ground tests, or in flight, their outputs are amplified, and finally recorded by an oscillograph. The over-all frequency response of the system is flat from zero

to several hundred cycles. Because the gain required is beyond capabilities of direct coupled amplifiers, a carrier system is used. To make possible the direct recording of either acceleration, velocity, or displacement on the final record, a choice of either single or double electrical integration is provided on each of twelve channels. Inasmuch as this type of equipment must be used for accurate quantitative measurements, as well as the qualitative type usually associated with seismic work, it was necessary to develop a calibrator. This machine has a smooth frequency range from zero to 50 cycles, and is able to move a total load of sixteen pounds, either horizontally or vertically, through accurately known amplitudes from zero to two inches, with acceleration harmonics of less than 5%.

Another problem was to design and build seismometers so small that they could be recessed into the tips of the propellor in the latest high speed wind tunnel. Accurate quantitative measurements of vibration down to one times gravity are possible, while at the same time the unit is unaffected by a centrifugal force equal to 650 times gravity. Much of this equipment must be unaffected in operation by temperature changes of $-70$ degrees to $+150$ degrees F.

It is doubtful if developments of this type could be successfully undertaken anywhere except in a large geophysical laboratory, because the background and experience of instrument development, together with the technique of interpreting the results, is a direct product of geophysics.

At the same time it has been possible to build up a background of experience, personnel and facilities that is of direct benefit in our major responsibility—geophysical exploration.

The critical necessity of increasing our petroleum reserves has been ably presented by other speakers. It is obvious that geophysics must share to a large degree in this responsibility.

From a practical point of view, the problem is being resolved along these lines:

First, we must make the most effective and intensive use of the tools we now have at our disposal. This responsibility falls equally on the geologist, the geophysicist and the executive management. Upon the geologist falls the task of guiding the campaign, and of making the most effective use of the information that is obtained. Upon the geophysicist falls the task of carrying out the program and aiding in the interpretation of the results. Upon the management, and this the point I particularly want to stress, lies the responsibility of providing the venture capital in the enterprise.

Second, we must improve the methods and techniques that now exist. We have made a diminishing amount of progress along this line in recent years. Part of this has been due to the low price of oil, with the consequent reduction in exploration activity until the last few months. But to an even greater extent it has been due to the natural difficulties of adding further improvements to methods and techniques that have already been intensively investigated. In this attack it is the geophysicist who must carry the major burden, and results will be largely the product of his resourcefulness. The encouragement and cooperation of the geologist and the management are nevertheless absolutely essential. It is my belief that while considerable further improvement may be expected in instruments, the greatest progress will be made in field techniques and interpretation of data. It is probably through the intensive improvement of the methods we now have available that the most progress will be made, and, therefore, no effort should be spared to carry this aspect of the problem forward.

Third, while every possible encouragement should be given to the development of new and so far untried methods of finding petroleum, I am not optimistic that anything radically new will come along in time to help us appreciably in the campaign that is just ahead. It would certainly be a mistake to wait for it. Most of the basic avenues of approach have been thoroughly explored, and they are either in active use today, or have been discarded. In any event, it is logical to believe that such developments from now on will be the result of long and painstaking research, rather than a stroke of intuition. Is it not possible that the availability of radically new methods of exploration at times when they were most needed in the past has, to some extent at least, been a fortunate coincidence, and that we have been getting more than our share of the breaks? Only time will tell, and at this moment "time is short."

This three-fold program does not differ in its essentials from the trend of policies in the past, except that we must now redouble our energies and resourcefulness, and then redouble them again. If it is to be carried through successfully it must be translated into men, materials and sustained effort.

Men and materials needed in exploration are not required in large numbers or amounts. Nevertheless, almost everything connected with exploration is of strategic importance elsewhere.

One of the biggest groups of problems, however, comes under the heading of sustained effort. It appears probable that with curtailed

or selective consumption of petroleum products, and increasing costs of operation and transportation, together with higher taxes, the profits of the petroleum industry may be substantially reduced. The venture capital to carry forward exploration has in the past been balanced against profits. Exploration activity, and particularly geophysics, has been among the first expenditures to be lopped off. The reasons are partly financial and partly psychological. We have been able to accommodate ourselves, even though with some difficulty, to these cycles of activity. Today, however, the problem is infinitely more complex. For example: the number of technically trained and experienced geologists and geophysicists is strictly limited, and if they are even momentarily released from their existing occupations they will be lost for the duration of the war. The funds for carrying forward research and development must also come from venture capital, although these expenditures are usually more stable than are those devoted to exploration. The importance of qualified and experienced personnel in this type of work is of equal importance, however. It is obvious that if once the exploration machine is stalled, it cannot be started again until after the emergency had passed.

I have complete confidence that the geologists and geophysicists of the petroleum industry will rise to this emergency. They have the resourcefulness, ability and energy to carry through this responsibility.

The financial decisions that will have to be made in the near future by the executive managements of our oil companies, and by the governmental agencies involved, however, will—to a large extent—dictate the future of our petroleum reserves for many years to come.

# THE RELATIVE PLACE OF EMPIRICAL AND ANALYTIC METHODS OF GEOPHYSICAL INTERPRETATION*

PAUL WEAVER†

ABSTRACT

The pioneer in geophysics has, in most cases, used empirical methods on his first jobs in the field. Frequently, such an initial campaign has been successful in that valuable evidence has been obtained as to the position of a new ore-deposit. Thereupon the method has received recognition so that additional parties have gone into field work; also, analytic methods have then been applied to show why the particular method succeeded in some cases and now far it would be likely to succeed in border-line problems.

After a discussion of the difference between empirical and analytic procedure, the author reviews the history of one geophysical project—the search for iron ore in the Lake Superior region by magnetic methods—describing the empirical efforts and the subsequent analysis. He then suggests that failures on certain other jobs might be less if the analysis be made earlier, and that there will be an economy, if this analysis be made before field work begins.

## INTRODUCTION

In the application of geophysics as an aid to prospecting, the pioneer has usually proceeded along empirical lines in selling successfully his services to his first client. This process begins with a demonstration that, in the vicinity of a geologic anomaly where commercial ore exists, there is also a measureable geophysical anomaly. The client is thereupon persuaded to make the same kind of geophysical measurements in an area where the same ore is sought.

The steps in this empirical method will be described in detail in the next paragraph, but first we should mention the other method whereby there can be developed an appropriate technique for a geophysical problem; this method is analytic, and proceeds by analyzing the kind of physical properties which characterize the ore or a geologic anomaly accompanying it, and computing how far away such properties can be measured, and by what instruments. The analytic method will be discussed in detail in a later paragraph. Too frequently in the past the analytic method has been applied to a geophysical problem only after the empirical method has been found to give vague results, whereas we feel some analysis should always precede field work. The purpose of this paper is to contrast the fundamental difference in ap-

* Presented at a dinner meeting of the S.E.G. held at the Colorado School of Mines during the period of the Annual Meeting, Denver, April 1942.

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proach by the two methods, and to show by reviewing the history of one type of geophysical surveying, how much time was lost and how serious errors in interpretation were perpetrated due to the fact that all early work was primarily empirical, and the analytic method was applied far too late.

## THE EMPIRICAL METHOD

The empirical method is applied in geophysics by successive steps which are briefly as follows:

1. An area is chosen where there is a known geologic anomaly, as remote as possible from others. A very simple case would be a formation-boundary or fault on the surface, separating outcrops of two different lithologic units of uniform rate of dip and uniform physical properties for some distance below the surface.

It would be desirable that the area chosen have mines or shafts so that access underground be possible, but this is not generally the case, and investigation is possible only on the surface or at very shallow depths.

2. An instrument which measures some physical property and therefore is described as a geophysical instrument, is then set up and readings taken at various points in this selected area of the geologic anomaly and also at points adjacent to it where no geologic anomaly is present.

3. A map or profile is platted to show the change in readings with the instrument from one geophysical set-up to another, and the pattern of these changes relative to the location of the geologic anomaly.

4. If there be some geophysical anomaly which can be inferred from these readings over the geologic anomaly and nowhere else on the map it is concluded that this particular instrument is capable of mapping this particular geologic anomaly, and the instrument is taken to other areas where a similar geologic anomaly is desired or suspected, but not yet demonstrable by other methods.

As has been stated in the first paragraph, this has been the most common procedure for the pioneer in the introduction of each geophysical method.

## THE ANALYTIC METHOD

An ideal procedure by the analytic method should comprise the following succession of steps:

1. Select a type of geologic anomaly associated with the ore-deposit for which search is being proposed. Ascertain what contrast in physical properties is to be expected within the anomaly and at the boundary of it with the non-anomalous neighborhood.

2. Determine the probable space-distribution of this contrast with respect to set-ups at which measurements would be feasible, and the mathematical formula to express the rate of change from set-up to set-up of the effect of the anomaly.

3. Analyze also the change from set-up to set-up of any background variation (the so-called noise level) in the same physical properties.

4. Design an instrument to measure the physical property or some function thereof, and give adequate precision, if possible, so that the measurements at a group of set-ups is applicable directly in the mathematical formula already derived.

5. Protect the instrument against background noise or other transients foreign to the primary measurement for which it was designed. To do this may frequently require controlled experiment or statistical treatment of preliminary field data.

6. Make field set-ups and compare the resultant geophysical profiles and maps with the ideal ones constructed for families of geological anomalies of the kind being sought, and determine if the field map reasonably fits one of this family. This step is obviously to a certain degree empirical.

Let us now consider a particular historical example. For this detailed review of the history we shall choose the magnetic method.

Certain naturally-occurring iron-bearing minerals were early recognized to manifest, more than practically any other rocks, those properties we now call ferromagnetism and paramagnetism. As soon as there was a demand for new iron-ore bodies, it was recommended that they be sought with some form of instrument utilizing a magnetic needle. The greatest areal mapping program of this kind was that undertaken in Northern Wisconsin, Michigan and Minnesota following the suggestion of Brooks.[1] The lands showing the sharpest magnetic anomalies were leased, but to the chagrin of many of the prospectors, some of the lands which were bought by speculators without the aid of magnetic surveys turned out to have larger deposits of the kind of iron ore which the furnaces wanted than were on the

[1] Geological Survey of Michigan, Vol. I, Part 1, 1873, Chapter VII.

lands selected by experiments on the basis of their magnetic surveys.[2] The result of many years of this empirical campaign of geophysical prospecting as a direct finding method was dispairingly expressed by H. L. Smyth in 1896 as follows:

"It may be asserted as a general proposition, the essential truth of which has been established by the experience of many years, that in the region referred to magnetic disturbances usually mean that magnetic iron ore in a workable deposit does not exist in the area of disturbance."[3]

Twenty-seven years later, in 1923, Hotchkiss[4] stated the perplexity still existing at that date in the following words:

"Far too little is known about the distribution of magnetite in rocks. . . . Whether magnetite acts like so much soft iron and therefore its magnetism is wholly induced by the earth's field; whether it acts like steel and possesses permanent magnetism . . .; or whether the magnetite in a rock may in part behave in one way and in part the other way, are questions we cannot answer until much research work has been done. . . . The author has found but two determinations of the effect of magnetite on weak fields like the earth's."

However, both Smyth and Hotchkiss found from field experience that magnetic surveys in the same area of Michigan, Wisconsin and Minnesota could help in interpreting the regional geology and in following outcrops under a cover of glacial drift, as well as in mapping certain tectonic features.

What was the trouble in Michigan, Wisconsin and Minnesota? In the first place, before Hotchkiss, no American realized—at least, none who were prospectors—that although iron-bearing minerals were paramagnetic, only magnetite and specular hematite had strong enough magnetic susceptibility to be readily distinguishable by their instruments. They did not consider the implications of the fact that the susceptibility of magnetite was so much greater than nearly all other common minerals that a small percentage of magnetite, say of the order of one-tenth of one per cent, in non-ferrous rocks gave a permeability greater than a commercial iron-ore of another iron mineral.

When was this first pointed out? To Mason, Slichter and Hay, in

[2] For an idea of the prospecting for iron at this period see Paul DeKruif, "Seven Iron Men," Harcourt, Brace and Co. 1929.

[3] U. S. Geological Survey, Monograph XXXVI, page 337, 1899.

[4] Amer. Inst. Min. & Metal. Eng. Trans. Vol. LXIX, page 38, 1923.

their laboratory investigations at Madison, should be given the credit. Slichter has reported briefly their modus operandi and their results,[5] and their approach was by the analytic method, as will be described later. However, before this group began their study of the subject, thousands of miles of traverse, under extremely difficult field conditions, had been run in the Lake Superior Region of the three states mentioned, with solar compass and declination-needle, with the ordinary dip needle, with the Thalen-Tiborg magnetometer and with the super-dip needle. From what Mason, Slichter and Hay found and, we all know now, this was a mapping of the concentration of a single mineral—magnetite, whereas what most of the prospectors were looking for was another mineral, the two being similar primarily only in that both were iron ores. Only if the magnetite had always been most abundant where the hematite, the other iron ore, was in commercial quantities, would the method have succeeded.

Now let us review briefly how the investigations were carried out by Mason, Slichter and Hay, as outlined by Slichter. He first states

"Magnetic susceptibility should be conceived as a multiplier which expresses the amount by which a material is capable of boosting the magnetic field above the normal value. The rocks, in fact, are magnetized by the earth's field. The strength of the magnetization induced is found to be equal to a constant times the strength of the earth's field, and it is precisely this constant which is the magnetic susceptibility of the rock in question. Magnetic susceptibility is a physical constant of material which may be accurately measured in the laboratory, and it plays the same basic role in magnetic surveys as does electrical conductivity in electrical ones, or density in gravitational measurements. We are interested, then, first in what values of the magnetic susceptibility may be assigned the various rock formations, and, later, how the combined factors of form, depth of cover, and of magnetic susceptibility influence the ability to recognize the characteristics of the peculiar hidden structure through magnetic measurements."[6]

He says further:

"Careful tests are recommended in order to establish whether, in the first place, a given formation is sufficiently uniform magnetically to form a magnetic unit, and, secondly, to establish the proper values of the susceptibility in the case."[7]

[5] L. B. Slichter, "Certain Aspects of Magnetic Surveying," A.I.M.E., Geophysical Prospecting, 1929, pp. 238–258.

[6] *Op. cit.*, p. 240.

[7] *Op. cit.*, p. 242.

These quotations briefly outline their procedure, which included—

1. The selection of a fundamental physical property, in this case magnetic susceptibility.

2. The computation of the mathematical formulae to express dependence of the effect at a distance: i.e., induced magnetism in the direction of the earth's field following an inverse square law.

3. Calculation of many thousands of values for set-ups over finite and infinite bodies of particular form, to determine what sensitivity of field instruments, spacing of set-ups, and value of magnetic susceptibility would give a discriminating value to a survey of an unknown body.

4. Laboratory determination of susceptibility of different minerals, to find which were sufficiently different from other minerals to be usefully the subject of a magnetic survey.

5. Do the field work as far as possible where the mineral sought would be uniform over the ore body.

This investigation of Mason, Slichter and Hay was in fact well towards completion just a short time after Hotchkiss stated how deficient we were in fundamental data about magnetite. They accomplished in this short time more than the fifty years of field work in Michigan, Wisconsin and Minnesota insofar as deciding to what extent iron-ore bodies could be located with magnetic measurements, and they did it at a fraction of the expense, because they proceeded by the analytic method.

As soon as magnetic surveys began to be made with instruments of great sensitivity, it became apparent that magnetic susceptibility is not the only magnetic property which can be utilized in geophysical work. When the paramagnetic substance is magnetized in the earth's field or in any other field, and subsequently moved to another magnetic field, or demagnetized, there is a lag in the response to the new field, and it was found that this lag in some cases is of sufficiently long time that it must be taken into account in making measurements of rocks previously magnetized. For example, the magnetic susceptibility of ordinary brick is low because the iron minerals formed during the process of firing the brick are mostly those of low susceptibility. However, brick will be found to possess polarity, that is, it retains the direction of magnetism, for a long time, of the earth's field in which it was fired, and this is also true of pottery. So that if rocks are in the earth's field and that field has changed through time, or if the rocks have been changed, either geophysically or through geological

processes, in addition to the magnetism which is induced by the present direction of the field, there is magnetism induced by the former direction of the field.

Appreciation of this situation led Lynton[8] to a development of the polar core orientation method of determining the direction underground of cores after they had been removed from a well. Although this is of second order in most cases compared to the magnetism in the present earth's field, an analytic study enabled Lynton to devise proper equipment for the measurement of samples of very weak susceptibility; and the method has proved useful in solving problems for which other methods require more cumbersome apparatus.

This is a very brief review of magnetic surveying, a single branch of geophysics, and does not attempt to take up the background problems involved in the work which are due to the fact that the earth's field is constantly changing, and that therefore some method of measuring this variation in background is necessary when magnetic work of precision is required. It is, however, in the opinion of the author, a striking demonstration of the ultimate economy of analytic methods of geophysical interpretation as compared to empirical methods; and the author believes that we should review the methods which we are now employing to see if we cannot study out in many areas some detailed analysis which will economize in field work. It would seem that in many actual surveys we are taking a great many field set-ups and using average values determined therefrom, because there are errors which appear to be inherent in individual measurements which are being averaged out or studied by the method of statistical analysis, whereas, it would seem possible to apply analysis to the problem first and see whether a greater degree of reliance cannot be placed upon individual observations by improvement in technique.

Chas. F. Kettering, in the *Saturday Evening Post* of March 28, 1942, has an article of which the title is "There is only one mistake: to do nothing." I am afraid we are making that mistake in some of our field work because we are doing nothing to apply additional analysis to our problem. In this article he has pointed out some of the problems of research in general, and he concludes:

"In almost every line of endeavor we confuse the real problem with the apparent problem. Before the Panama Canal was built, everyone thought it would be a simple engineering problem of moving millions

[8] Bull. Amer. Assoc. Petrol. Geol., Vol. 21, No. 5, p. 580, May 1937. GEOPHYSICS, Vol. III, No. 2, p. 122, April 1938.

of tons of earth. That's what the French thought, and because they didn't find the real problem they failed. The real problem was a biological one and was concerned with the habitat of two female mosquitos, the *Stegomyia* and *Anopheles*. . . . This was the only thing we knew that the French didn't know. We had found the obscure problem which meant the difference between success and failure."

The problem in geophysics differs from the situation described by Kettering because a complete mathematical analysis of the situation should show all of the facts involved and should at least tell us what type of mathematical analysis we need, but in many geophysical problems the number of different boundaries are so great that the mathematical analysis may be impossible to handle. Even recognizing these cases, it would still be the thought of the author that we should review from the analytic side not only our present methods, but any other possible lines of attack, with a view of reducing the amount of field work per unit area, thereby saving personnel, transportation and overall cost in the search for new oil supplies.

## DISCUSSION

Mr. Weaver's paper is very timely in bringing our attention back to considerations which probably have been overlooked or forgotten in the routine application of geophysical surveys. In the early days of a method, careful thought is apt to be given to the various controlling factors and limits which can influence the results. When a method becomes well established, these controls and factors tend to be forgotten in routine applications and these applications may well run beyond reasonable limits. Thus, in the later stages of development we probably tend to become more empirical and less analytical and therefore Mr. Weaver's remarks should serve to direct our thoughtful attention back again to the analytical phases of our work. This is true to the extent that a definite distinction can be made between analytical and empirical approaches, both of which have a large part and a proper balance in any well conducted geophysical (or other scientific) activity.

Whether or not exploration (or any technical problem) is approached empirically or analytically will depend to a considerable extent upon the instrumentation available and the hands in which it is used. If the instruments are comparatively simple and are used by so-called "practical" men, the procedure is apt to be highly empirical. This is well illustrated by the magnetic surveys carried out by the Merrit Brothers as told by DeKruif. These men, although untrained in science, could operate simple magnetic instruments reasonably well, but had no more than the simplest conception of the significance of the quantities measured. Their approach, therefore, was wholly empirical and intuitional and is probably representative of that of many of the men who made these early magnetic measurements.

In the history of geophysical prospecting in the oil industry, a clear division between the analytical and empirical approach is not possible. The considerations which must be applied will contain both factors and a reasonable balance between them must be maintained for the best progress.

The fundamental properties on which gravity prospecting is based (i.e., the density contrasts of rocks) are simpler and less apt to be ambiguous than are the magnetic properties. This has led to a somewhat more reasonable history of this method.[1] However, density conditions which now seem simple have been misleading, as when early torsion balance exploration for salt domes got a false start (from an empirical test) when the first work[2] looked for maxima and missed the significance of minima.

On the other hand, some early gravity work based on an analytical approach by competent men left puzzling and uncertain results. For instance, the series of small groups of gravity stations made by the U. S. Coast & Geodetic Survey to test the ideas of David White that local geologic structures should have recognizable gravity anomalies failed quite completely, in several cases, to show the expected results. It is now evident that these failures were due in part to unrecognized sources of error in the measurements (although statistical analysis indicated that the values were good) and in part to the fact that the expected anomalies, although actually present, are in a complicated setting which could not be appreciated until an extensive coverage with much more closely controlled surveys was available. For instance, the three pendulum stations which were expected to show the gravity anomaly at the Healdton field (Carter County, Oklahoma) plot into almost a uniform gravity slope across the field (when the corrected values from later observations are used; one of the original observations was seriously in error). An anomaly somewhat similar to that which White probably anticipated is actually present but is largely masked by a strong regional effect and is shifted somewhat from the center of the shallow structure of the oil field.

This is illustrative of the situation in many cases where one might attempt an analytical approach to the question of the utility of a given geophysical proposal. In so many cases the lack of sufficient geologic knowledge in advance prohibits any amount of analytical work from deducing the geophysical effects which might be observed and their utility in terms of added structural or other geologic information. We simply do not know the physical factors well enough and have no reasonable way to obtain them to anticipate the geophysical results. About the only way to answer the question is to empirically test a sample of the area in question or a known example of the type of subsurface anomaly anticipated with a geophysical survey and see what results it gives.

In some cases an analytical approach might well lead to a result which, if logically followed, could act only as a deterrent to the proposed geophysical work. For instance, in 1930 any analysis that might have been made of the question of obtaining reflections in the homogeneous sand and shale section of the Gulf Coast probably would have argued against the utility of such work. Then it would have been only those who didn't know any better that would have had the courage to take a seismograph into the area just to see whether it would work or not. There are many cases in the history of science where important discoveries have been made by men who have tried things because they didn't know analysis showed that the proposed scheme would not work.

Now, taking the other stand, I would like to mention one aspect of gravity interpretation which still suffers from an empirical approach where a small amount of analysis would be very useful. Many geologists still tend to make simple interpretations of

[1] E. A. Eckhardt, "A Brief History of the Gravity Method of Prospecting for Oil," GEOPHYSICS, Vol. 5, No. 3 (July, 1940) pp. 231–242.

[2] E. E. Rosaire, "Prospecting Effectiveness," GEOPHYSICS, Vol. 6, No. 4 (Oct. 1941), p. 438.

gravity (and magnetic) anomalies in terms of a one to one correspondence with structure. In many cases the application of very elementary analytical considerations of the probable density contrast, structural relief and corresponding gravity amplitudes would show that the simple interpretation does not fit the analytical requirements by perhaps a whole order of magnitude. In such cases very simple calculations could eliminate many geologic interpretations and proposals for actions based thereon and possibly save large expenditures which might be made in vain from simple empirical considerations.

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Gulf Research and Development Company

Mr. Weaver's paper is a challenge to analyze our present methods of turning geophysical data into drill sites and to question whether these methods make full use of scientific knowledge. The development of most applied science has been from the empirical to the analytic. To take medicine as an example; primitive peoples had an equal faith in their witch doctors as in their herbal remedies. It required the skilled observation of the scientist to prove that the witch doctor's dance was less curative than the quinine, and yet 400 years after Hippocrates civilized peoples were still casting out evil spirits from the sick. When and how did exploration geophysicists graduate from the necromantic era and did we leave too many Hippocrates' unheeded?

The history of gravimetric prospecting in the oil industry strangely parallels that of magnetic prospecting outlined by Mr. Weaver. The foundations were well and truly laid by von Eotvos who, by 1910, had developed a suitable torsion balance and had shown how the resultant observed gradients could be interpreted. His approach was largely analytic which led him to appreciate the precision necessary in his instrument and the type of geological problem best suited to the method. Soon after World War I Dr. Barton visited Europe to study the application of geophysical methods to oil prospecting and brought back with him the Eotvos torsion balance. Barton must have become familiar with the classical work of von Eotvos and others in the North German Salt Basin and so one must assume that the preconceived idea in the minds of Gulf Coast pioneers was the significance of minima in a salt basin; this significance was established by analysis and confirmed by field measurements. It happened that the first survey made in the Gulf Coast was at Spindletop, a shallow dome having heavy cap rock, and a prominent local maximum was observed. Maxima were in vogue and minima were relegated to the files; empiricism held sway. A few die-hard analysts still clung to the significance of minima and dry holes were drilled on several such prospects, including Lost Lake and Roanoke, between 1925 and 1927. Fortunately, the method had sufficient basic merit to survive this initial unscientific approach and by 1929 data were being subjected to analytical treatment by quantitative methods published by Barton and others.

The first question asked regarding a new geophysical method is usually "How does it work in a known field?" Thus most new methods are first tried out on producing fields and anomalies are usually mapped. Without more ado the method is then too frequently employed on an extensive scale to search for similar anomalies even though the anomalies may have no logical connection with an undisturbed accumulation of oil; this was the case in some early magnetic surveys where the minima observed were due to casing. Certain methods, of which geochemical prospecting is a good example, are based on observed phenomena which can be analyzed only if we possess information on physical

states, such as cementation and fracture, which is hardly ever available. About all that analysis can achieve under such circumstances is to test the logical basis of the method.

The ability and knowledge necessary to analyze geophysical data is our unique professional attribute; our professional opinions should reflect this fact.

FRANK GOLDSTONE
Shell Oil Company

The main contention of Mr. Weaver that mathematical and physical analysis of the problems involved should precede and accompany the field application of any geophysical method of prospecting rather than a purely empirical or trial-and-error approach is eminently sound, in my opinion. We may imagine where the electrical industry would be today if it had been forced to rely on trial-and-error methods of development rather than on the analysis of Kelvin, Maxwell, Heaviside, Steinmetz and their successors.

The petroleum industry owes a great debt to such pioneer analysts in the geophysical field as Wiechert, Galitzin, Knott, Zoeppritz, Eotvos and others. Geophysics cannot dispense with analysis today; and the earlier it is applied to a problem the less will be the waste. Of course, it is true, as someone has said, that mathematics is a sort of sausage machine and that you get out of it the very same meat you put into it. It is true also that some geophysical meat is far too tough for our ordinary mathematical grinding machines. But in so far as the grinding succeeds we shall render the tough meat more edible; and since we can control both the meat and the machine we can make the product in the form of answers to problems very definite.

JAMES B. MACELWANE, S.J.
Saint Louis University

I agree with Mr. Weaver in the relative merits of an analytical procedure as opposed to an empirical procedure in the analysis of geophysical data. However, the pioneer in geophysical exploration in entirely unexplored areas may be obliged to resort to the empirical approach to his data. This he may do sometimes to his advantage, but his errors come in applying the method over too large a territory. Certainly, he should use the empirical method with caution and abandon it in favor of the analytical method when data are available for such procedure.

I am acquainted with the early exploration in central Kansas where magnetic data played an important part. An extended survey by the magnetometer in Barton, Stafford, and adjoining counties outlined a positive magnetic anomaly covering portions of Barton and Stafford Counties. A clue to the proper interpretation of this anomaly was suggested after two wells had been drilled—one on the anomaly and one off of it. This clue led to a chain of events which ultimately resulted in the discovery of the Ellinwood and Richardson pools.

Again, a similar magnetic survey covering portions of Barton and Rush Counties outlined a negative magnetic anomaly and the clue to its interpretation was suggested by the drilling in of the first gas well. The major feature of the area is well outlined by the negative magnetic anomaly. It is important to this discussion to note that the two anomalies mentioned are less than thirty miles apart. One is a positive anomaly and the other is a negative anomaly. The major axis of the positive anomaly trends northeast and southwest, and the major axis of the other trends northwest and southeast.

These two anomalies were both helpful in predicting the possible location and extent of oil and gas fields. The axis of one was approximately at right angles to the other. One was positive and the other was negative. Obviously, any empirical procedure in handling the data over the entire area would have been wrong; however, limiting the method to the local anomaly, useful information was obtained.

A striking positive magnetic anomaly exists in south-central Phillips County, Kansas. This anomaly is so striking that it invited attention and resulted in core drill exploration. A single row of exploratory holes proved that the anomaly was not coincident with any structural anomaly present in Cretaceous beds. However, it was offset two to three miles from a very definite anticlinal fold in the Cretaceous beds. Subsequent development proved this fold to exist in Pennsylvanian horizons. An extended core drill pattern of core holes proved the presence of the Cretaceous structure the entire length of the magnetic anomaly, but all points offset the same distance. A similar method of exploring another anomaly in this same region proved no such relation existed.

If it is necessary to use the empirical method of approach in the handling of geophysical data, it should only be applied locally.

R. CLARE COFFIN
Stanolind Oil and Gas Company

Mr. Weaver has very ably presented the weakness of the empirical method of approach to geophysical prospecting problems. I am in hearty accord with his plea for the more intensive use of analysis in the consideration of both new and old prospecting methods.

It was kind of Mr. Weaver to select an example from the field in prospecting for ore. We who are prospecting for petroleum need hardly be reminded that equally horrible examples of uncontrolled empiricism might have been selected from our field.

It seems probable that the popularity of the empirical method of approach is due largely to two factors, one of which is technical, the other, psychological. The paucity of fundamental data regarding the properties of earth strata and their relationship to accumulations of commercially valuable products, plus the difficulties involved in the analytical attack on most prospecting problems, makes the empirical approach often seem an attractive short cut even to well-trained technical men. This despite past experience indicating that the apparent short cut is often a blind alley.

The psychological factor I have in mind may equally well be termed an economic factor. Whatever the reason may be, it is evidently a fact that the prospector finds less difficulty in obtaining financial support for empirical trials of new methods, than in obtaining financial aid for fundamental studies necessary to the analytic approach. As long as this condition exists, the scientific prospector may turn it to his advantage by considering empirical tests as sources of data for future analysis; and he may in the course of such tests, find an opportunity for some judicious field experimentation.

W. T. BORN
Geophysical Research Corporation

# GRAVITY AND MAGNETIC CALCULATIONS*

L. L. NETTLETON†

In the earlier geophysical literature, many schemes were published for the calculation of gravity and magnetic effects. For the most part these were either the curves for the effects of certain definite geometric bodies or various charts and diagrams by which the effects for a body of any shape could be determined graphically. It is probable that these schemes have had comparatively little actual application in the interpretation of magnetic and gravity surveys. This is because of the fact that unless certain controls other than the gravity and magnetic data are available the inherent ambiguities of the physically possible distributions of material which can produce the observed effects make an accurate calculation meaningless, even though the geophysical data may be of any desired precision. Furthermore, it is often possible to calculate, from rather generalized forms, geophysical effects which are in agreement with those observed within the precision of the observations. In fact, unless two conditions are fulfilled, *i.e.*, (1) observed data are of high precision and spaced at distances substantially less than the horizontal dimensions or depth of the disturbing body, and (2) some other control is available, there is little point to using any of the more refined methods of calculation.

Since the two conditions just mentioned are fulfilled only with quite detailed surveys in areas with some drilling (or other geophysical) control, the effects from certain generalized geometric forms are very often close enough to those observed so that they give all the information wnich can be usefully applied in connection with the interpretation of reconnaissance surveys. The purpose of this paper is to present formulas and curves for a few geometric bodies in generalized dimensionless form by which specific cases can be readily calculated. The formulas and basic curves are selected and arranged (on the basis of their use over a number of years) so as to make them most useful.

The basic formulas for most of the work which follows have been known for years and are in the standard text-books on potential theory, electricity and magnetism or geophysics. It is only in the

* Presented at the Annual Meeting, Denver, Colorado, April 24, 1942.

† Gulf Research & Development Co., Pittsburgh, Pennsylvania.

selection and arrangement of these into a uniform system and in expressing the constant terms in units familiar and convenient for geophysical calculations that this paper makes any contribution.

The magnetic effects are given only for the vertical field component from vertically polarized bodies. These cases, of course, are greatly simplified over actual occurrences in nature where, in general, the magnetizing field is not vertical. However, they approximate actual conditions closely enough to be useful in indicating the approximate magnitude and general shape of expected effects as ordinarily measured with the vertical magnetometer and are very much simpler to use than the complete expressions, taking into account the inclination of the direction of polarization and the strike of elongated bodies with respect to the magnetic meridian.

For each geometric form considered, the formulas for the gravity and magnetic effects are given in parallel columns. It is convenient to reduce the geometric part of the formulas to a dimensionless expression in terms of the ratio $x/z$ where $x$ is the horizontal component of the distance from the center (usually) of the body to the point at which the effect is to be calculated and $z$ is a depth parameter of the body. A curve is then plotted of this geometric part which is applicable to any body of the form under consideration. The other factors are assembled into a numerical coefficient which is determined by the dimensions and physical properties of the particular body being considered. The desired effect at a given point is determined as the product of a value read from the general curve by the coefficient evaluated for the particular body.

For gravitational effects the coefficient involves the size (*i.e.*, scale) of the body and the density contrast. For ease in making geophysical calculations the various constant numerical coefficients and conversion factors have been assembled to give calculated effects in milligals for linear dimensions in 1000 foot (kilo-feet) units. The dimensions enter the coefficients for the magnetic expressions only as ratios so that the scale does not affect the magnitude but only the horizontal spacing of the calculated effects.

In several cases, the formulas are developed with the approximation that the mass or magnetic material is concentrated to a surface distribution on the median plane of a body of finite thickness which it represents.[1] This leads to a very great simplification of the formulas

[1] See Tsuboi and Fuchida, Earthquake Res. Inst. of Tokyo Bulletin, Vol. XV, No. 3, pp. 636–642 (1937), for an extended treatment of this approximation. [EDITOR.]

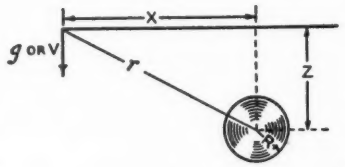
and the approximate values thus obtained are close enough to those obtained with the much more complicated rigorous formulas to serve for most geophysical calculations. The utility of this concept for geophysical applications does not seem to have had the appreciation which it deserves.

The notation is uniform, according to the following definitions:

$x$ = horizontal distance on ground surface from a point above the center (usually) of the disturbing body to the point at which the effect is calculated.
$z$ = depth from surface to the center (usually) of the disturbing body.
$r$ = distance from the center (usually) of the disturbing body to a point at which an effect is calculated.
$R$ = radius of disturbing body.
$t$ = thickness of disturbing body (for lamellar forms).
$\gamma$ = gravitational constant = $6.67 \times 10^{-8}$ c.g.s. units.
$\sigma$ = density contrast in c.g.s. units.
$I$ = magnetic polarization contrast (assumed vertical) in c.g.s. units (for magnetization by earth's field, $I = kH$, where $k$ = susceptibility contrast, $H$ = vertical component of earth's field.)
$g$ = calculated gravity effect (in milligals in final formulas).
$V$ = calculated magnetic effect (in gammas in final formulas).

*The Sphere*

The sphere is the simplest geometric form for which geophysical effects can be calculated and will serve to illustrate the methods which are applied uniformly for the various forms considered. Therefore, the mathematical steps are shown in more detail than in most of the other cases which follow. Of course, masses in nature for which gravity or magnetic effects might be desired are never spherical, but in any case where the horizontal dimensions of the body being considered are substantially less than the depth, surprisingly close approximations to the gravity and magnetic effect can be made on the basis of its approximation as a sphere. The principal applications are to gravity effects over salt domes and magnetic effects of plugs or intrusions.




*Gravity*

$$g = \frac{4\pi R^3 \gamma \sigma z}{3r^3}$$

$$= \frac{4\pi R^3 \gamma \sigma}{3z^2} \cdot [1 + x^2/z^2]^{-3/2}.$$

Putting in $\gamma = 6.67 \times 10^{-8}$ c.g.s. units, expressing $R$ and $z$ in units of kilo-feet and $g$ in milligals, we have

$$g = \frac{8.52\sigma R^3}{z^2} f_1\left(\frac{x}{z}\right)$$

$$= K f_1\left(\frac{x}{z}\right)$$

where

$$f_1\left(\frac{x}{z}\right) = [1 + x^2/z^2]^{-3/2},$$

which is plotted as Curve 1 of Fig. 1, and

$$K = \frac{8.52\sigma R^3}{z^2}.$$

*Magnetism*

$$V = \frac{4\pi R^3 I}{3} \cdot (2z^2 - x^2)(z^2 + x^2)^{-5/2}$$

$$= \frac{8\pi R^3 I}{3z^3} \cdot [1 - x^2/(2z^2)](1 + x^2/z^2)^{-5/2}.$$

Combining the numerical factors, expressing $I$ in c.g.s. units, and $V$ in gamma, we have

$$V = 8.38 \times 10^5 \frac{R^3 I}{z^3} f_2\left(\frac{x}{z}\right)$$

where

$$f_2\left(\frac{x}{z}\right) = [1 - x^2/(2z^2)](1 + x^2/z^2)^{-5/2},$$

which is plotted as Curve 2 of Fig. 1, and

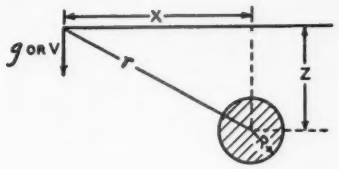
$$K = 8.38 \times 10^5 \frac{R^3 I}{z^3}.$$

* L. L. Nettleton, Geophysical Prospecting for Oil, McGraw-Hill, 1940, p. 103.

* *Ibid.*, p. 208.

*The Horizontal Cylinder*

An infinite horizontal cylinder also does not resemble any geologic structure. However, in any case of a long structure or mass unit, the horizontal dimension of which, in the cross section, is less than or not much greater than the depth, a fairly close approximation can be made by calculating the effects from a horizontal cylinder.




*Gravity*

$$g = \frac{2\pi R^2 \gamma \sigma z}{r^2}$$

$$= Kf_3\left(\frac{x}{z}\right)$$

where

$$K = \frac{12.77\sigma R^2}{z}$$

(to give milligals when $R$ and $z$ are in kilo-ft.), and

$$f_3\left(\frac{x}{z}\right) = (1 + x^2/z^2)^{-1},$$

which is plotted as Curve 3 of Fig. 1.

A table for reducing the effect calculated for an infinitely long or "two dimensional" body to that for a body of finite length is given in Nettleton *op. cit.*, p. 117. This table was originally calculated by S. Hammer.

* *Ibid.*, p. 108.

*Magnetism*

$$V = 2\pi R^2 I \cdot (z^2 - x^2)(z^2 + x^2)^{-2*}$$

$$= Kf_4\left(\frac{x}{z}\right)$$

where

$$f_4\left(\frac{x}{z}\right) = (1 - x^2/z^2)(1 + x^2/z^2)^{-}$$

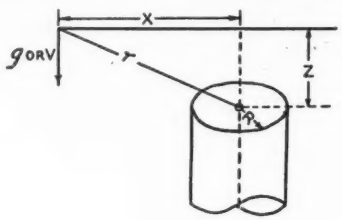
which is plotted as Curve 4 of Fig. 1, and

$$K = 6.28 \times 10^5 \frac{R^2 I}{z^2}.$$

* *Ibid.*, p. 209.

*The Vertical Line Element*

A vertical line element can be used to approximate a vertical cylinder for which the horizontal dimension is considerably less than the vertical dimension. Appropriate geologic examples are a narrow salt dome or a volcanic plug. The formula are given for the case in which the bottom of the cylinder is at infinite depth.




*Gravity*

$$g = \pi R^2 \gamma \sigma (x^2 + z^2)^{-1/2} *$$

$$= K f_5\left(\frac{x}{z}\right)$$

where

$$f_5\left(\frac{x}{z}\right) = (1 + x^2/z^2)^{-1/2},$$

which is plotted as Curve 5 of Fig. 1,

and $$K = \frac{6.39\, R^2 \sigma}{z}.$$

*Magnetism*

$$V = \pi R^2 z I/(x^2 + z^2)^{3/2} *$$

$$= K f_1\left(\frac{x}{z}\right)$$

where

$$f_1\left(\frac{x}{z}\right) = (1 + x^2/z^2)^{-3/2}$$

which has the same form as the gravity effect for a sphere and is plotted as Curve 1 of Fig. 1, and

$$K = 3.14 \times 10^5 \frac{R^2 I}{z^2}.$$

The above expressions can be used for cylinders of finite length (top at depth $z_1$ bottom at $z_2$) by simply subtracting the effect calculated for depth $z_2$ from that calculated for depth $z_1$.

* A. S. Ramsey; An Introduction to the Theory of Newtonian Attraction. London: Cambridge University Press, 1940, p. 30.

* C. A. Heiland; Geophysical Exploration, Prentice-Hall, 1940, p. 374.

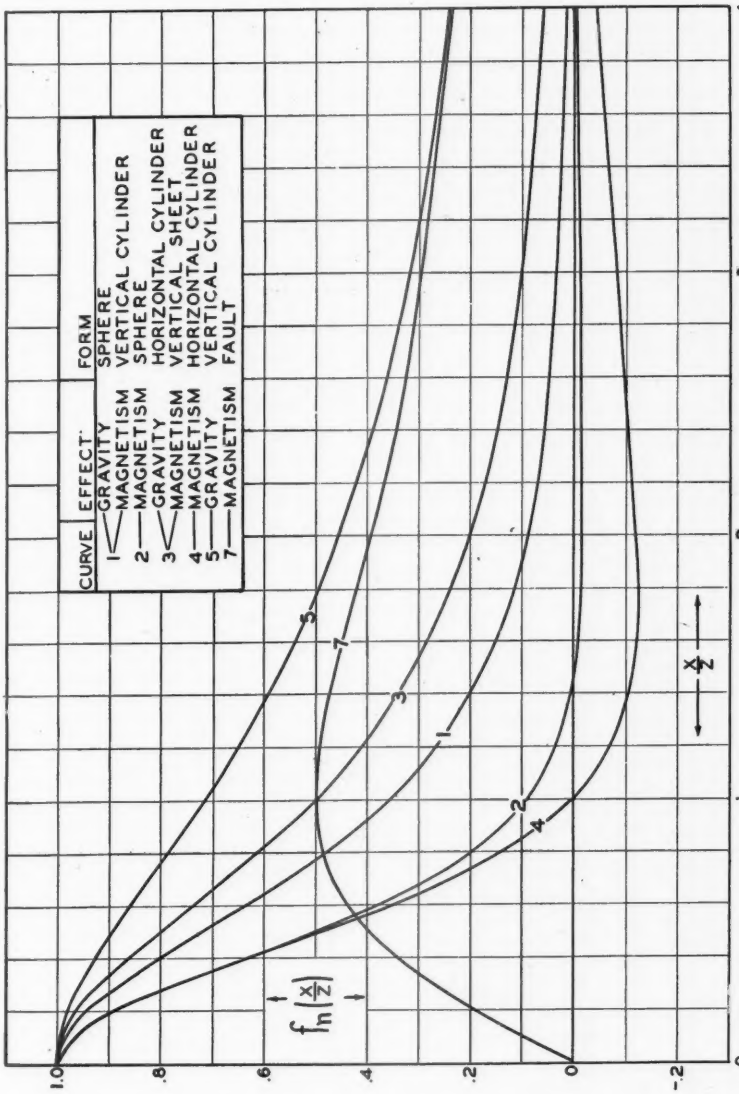
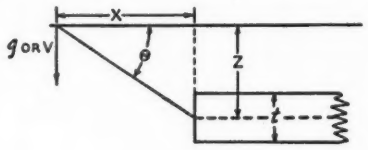



FIG. 1. "Master Curves" for calculating gravitational and magnetic effects for various geometric forms.

*The Vertical Fault (approximated by a horizontal sheet)*

The gravity and magnetic effects of a semi-infinite horizontal layer of finite thickness (the edge of which corresponds to a vertical fault) can be expressed quite simply on the assumption that the material is condensed into a thin sheet at the central plane of the body. The approximation is surprisingly close, even for bodies of considerable thickness. With a thickness of half the mean depth, the error at any point for gravity is less than 1% and for magnetism is less than 7%.




*Gravity*

$$g = 2\gamma\sigma t\theta$$

$$= 2\gamma\sigma t\left(\frac{\pi}{2} + \tan^{-1}\frac{x}{z}\right)^{*}$$

$$= Kf_6\left(\frac{x}{z}\right)$$

where

$$f_6\left(\frac{x}{z}\right) = \frac{1}{2} + \frac{1}{\pi}\tan^{-1}\frac{x}{z},$$

which is plotted as Curve 6 in Fig. 2, and

$$K = 12.77\sigma t.$$

* Nettleton, *op. cit.*, p. 113.

*Magnetism*

$$V = 2Itx(x^2 + z^2)^{-1*}$$

$$= Kf_7\left(\frac{x}{z}\right)$$

where

$$f_7\left(\frac{x}{z}\right) = \frac{x}{z}(1 + x^2/z^2)^{-1},$$

which is plotted as Curve 7 of Fig. 1, and

$$K = 2 \times 10^5 \frac{It}{z}.$$

* *Ibid.*, p. 212.

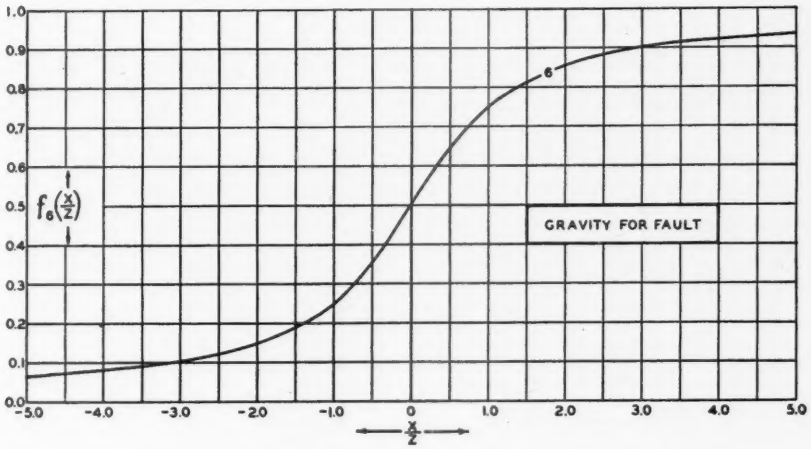



FIG. 2. "Master Curve" for calculating gravitational effect of a fault.

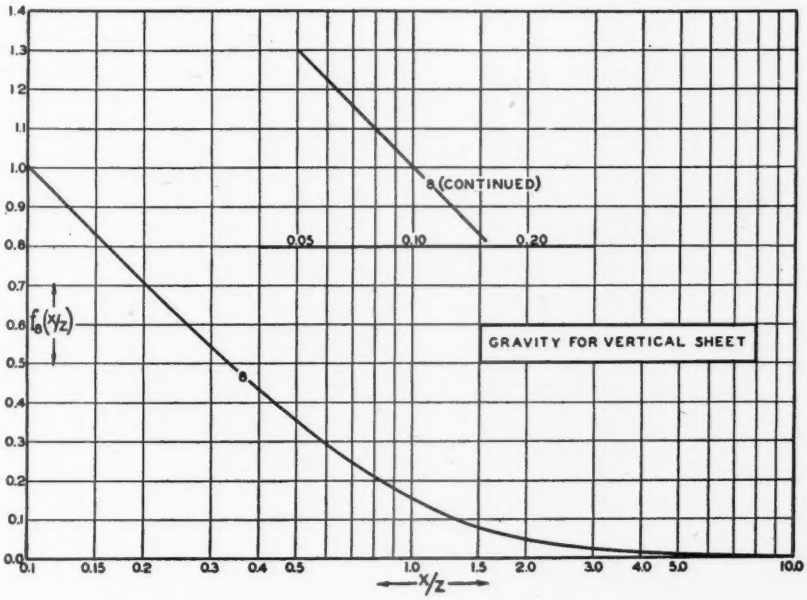
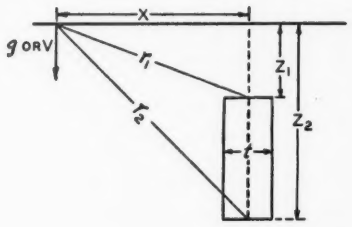



FIG. 3. "Master Curve" for calculating gravitational effect of a thin, vertical sheet.

*The Vertical Sheet*

Expressions for a vertical sheet are useful in approximating effects which might be caused by vertical dikes. As in the case of the horizontal sheet, the effects are calculated as if the matter were condensed onto a thin lamina, but this approximation is satisfactory as long as the thickness is rather small compared with other dimensions and distances to the point at which the effects are to be calculated.




*Gravity*

$$g = 2\gamma\sigma t \ln (r_2/r_1)^*$$
$$= K[f_3(x/z_2) - f_3(x/z_1)]$$

where

$$f_3\left(\frac{x}{z}\right) = \log \sqrt{1 + z^2/x^2},$$

which is plotted in Fig. 3, and

$$K = 9.36\,\sigma t.$$

* Derived by T. A. Elkins, Gulf Research & Development Co.

*Magnetism*

$$V = 2It[(z_1/r_1^2) - (z_2/r_2^2)]^*$$
$$= K_1 f_3\left(\frac{x}{z_1}\right) - K_2 f_3\left(\frac{x}{z_2}\right)$$

where

$$f_3\left(\frac{x}{z}\right) = (1 + x^2/z^2)^{-1},$$

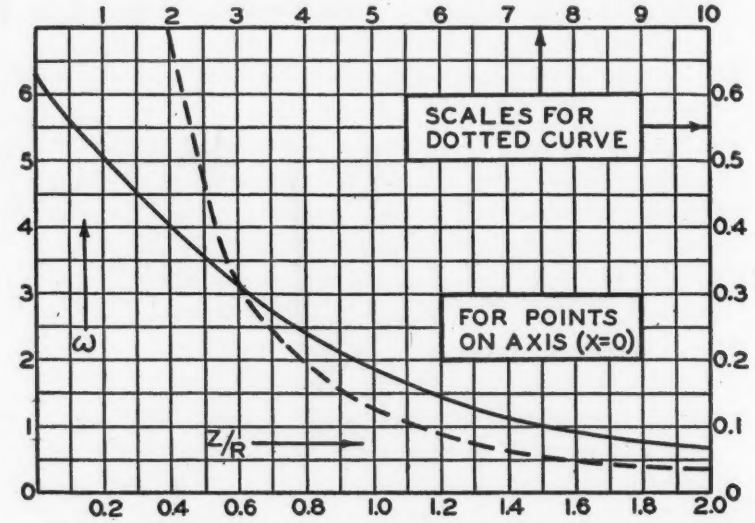
and has the same form as the gravity effect for a horizontal cylinder which is plotted as Curve 3 of Fig. 1, and

$$K_1 = 2 \times 10^5 I \frac{l}{z_1};$$

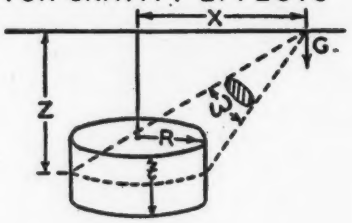
$$K_2 = 2 \times 10^5 I \frac{l}{z_2}.$$

* J. J. Jakosky. Exploration Geophysics. Times Mirror Press, Los Angeles, 1940, p. 118.

# SOLID ANGLES FOR HORIZONTAL CIRCULAR DISCS

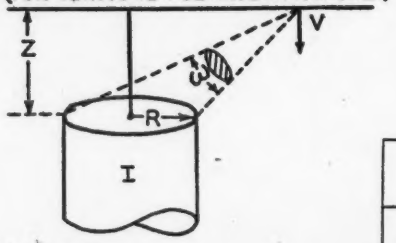



FOR GRAVITY EFFECTS

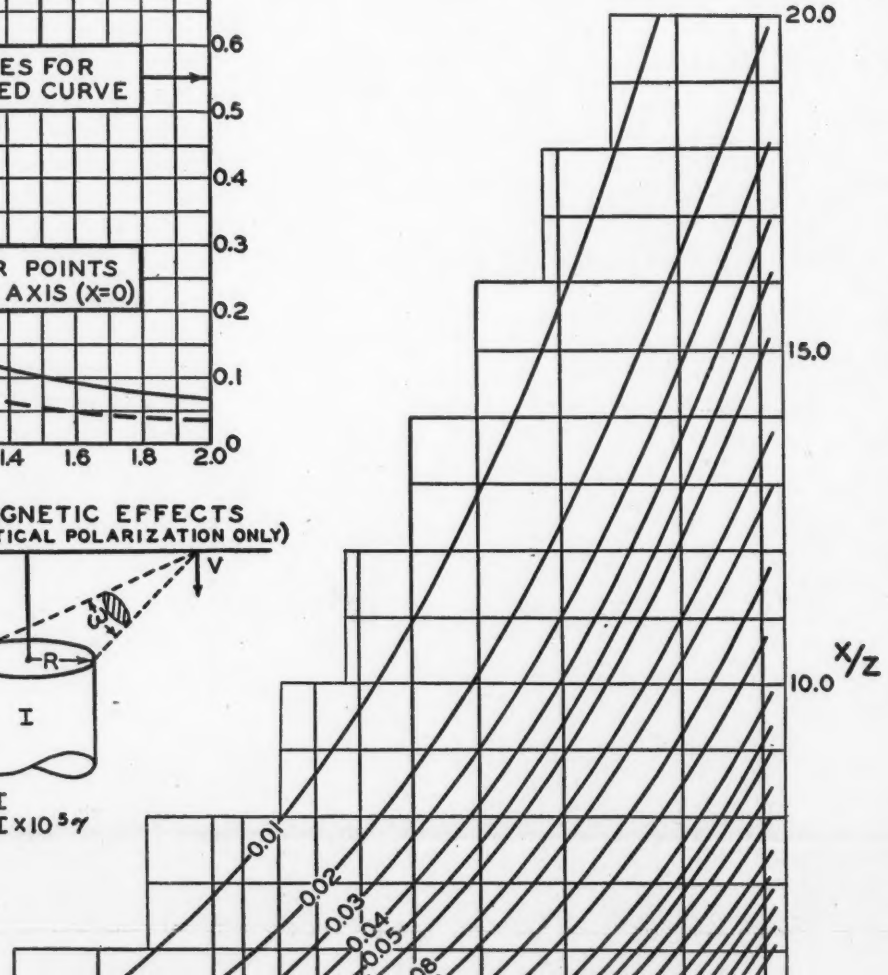



$G = 2.03\ \omega\sigma t$

FOR MAGNETIC EFFECTS
(FOR VERTICAL POLARIZATION ONLY)




$V = Z = \omega I$
$= \omega I \times 10^5 \gamma$



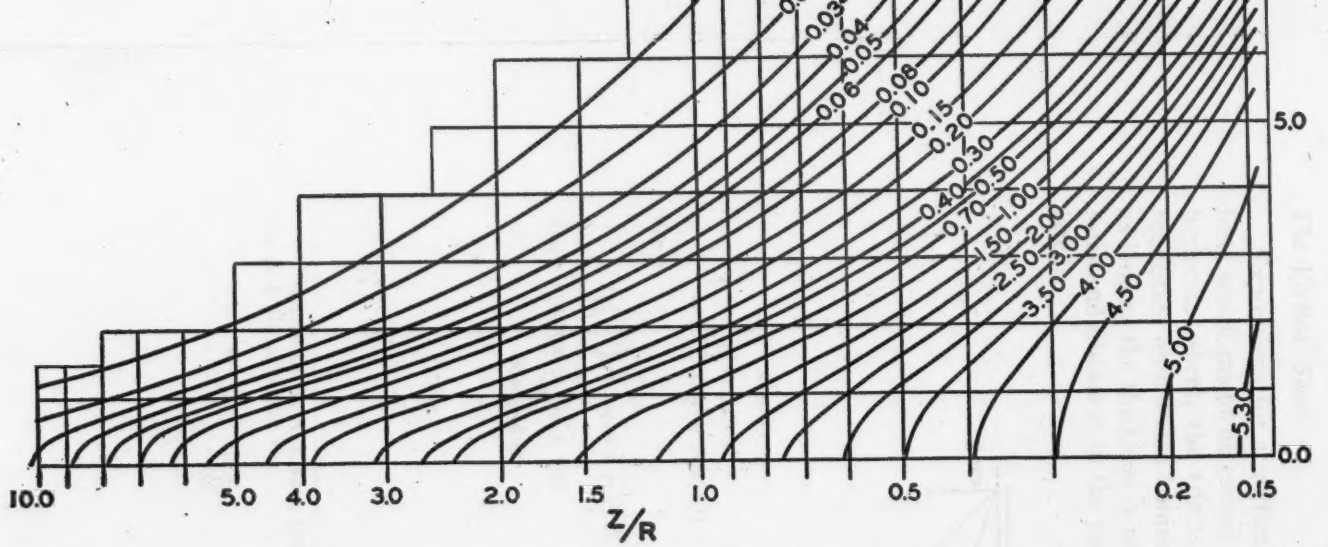



FIG. 4. Solid angle chart for calculating gravitational and magnetic effects for discs and cylinders, respectively. (Based in part on Bice Pelini, Atti Accad. Lincei. Classe sci. fis. mat. nat. 12, 216–222 (1930) and in part on unpublished graphical calculations, by H. M. Evjen, at Gulf Research & Development Co.)

*Solid Angles*

The vertical gravity effect of a thin horizontal lamina is directly proportional to the solid angle subtended, at the point being considered, by the boundary of this lamina. For a body with a thickness less than about half its mean depth, its gravity effect can be approximated closely enough[2] for most geophysical purposes by considering the mass to be condensed upon its median plane and calculating the effect in terms of the solid angle subtended by the boundary on that plane. For a vertically magnetized, vertical cylindrical body, the volume magnetization can be considered as replaced by a surface magnetization of its upper and lower faces. For each such face the magnetic effect at the point being considered is proportional to the solid angle subtended; hence, the magnetic effect of the cylindrical body is proportional to the difference between the solid angles subtended by its upper and lower faces.

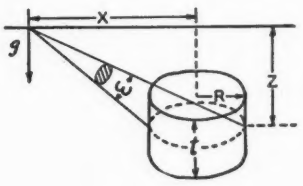
Calculation of solid angles for even simple boundaries is mathematically difficult but they can be calculated for circles. A chart giving solid angles for circles over a considerable range is given by Fig. 4. This is useful for calculating gravity effects of any body which can be approximated by horizontal circular slabs (such as a salt dome) or for vertical magnetic effects of any body with a circular cross section.

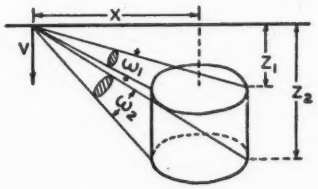
[2] The error in the effect calculated by the solid angles will depend on the ratios $R/z$ and $t/z$. For a point on the axis and for $t/z=0.5$, the errors are as follows:

| $R/z$ | *error* |
|---|---|
| 0 | −6% |
| .5 | −4% |
| 1 | −2% |
| 2 | −0.5% |

(Calculated by S. Hammer, Gulf Research & Development Co.).

*Vertical Circular Cylinder*




*Gravity*

$g = \omega\gamma\sigma t$*
$= 2.03\,\omega\,\sigma t$

Values of $\omega$ can be read from the solid angle chart (Fig. 4) from the ratio $z/R$ (which is constant for any given case), and the ratio $x/z$.

*Magnetism*

$V = I\,(\omega_1 - \omega_2)$*
$= I \times 10^5\,(\omega_1 - \omega_2)$ gamma

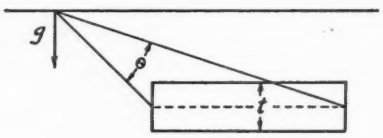
where $\omega_1$ and $\omega_2$ are the solid angles subtended by the upper and lower faces, read from the chart, Fig. 4.

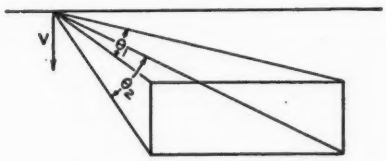
* Ramsey, *op. cit.*, p. 36.

* Nettleton, *op. cit.*, p. 216.

*Two Dimensional Slab*

For a horizontal plate of finite width and infinite length, the solid angle is simply $\omega = 2\theta$ where $\theta$ is the angle (in radians) subtended by the edges of the slab. This gives the following simple formulas.




*Gravity*

$g = 4.07\,\theta\sigma t$

*Magnetism*

$V = 2I \times 10^5\,(\theta_1 - \theta_2)$

*Summary of Formulas and Index of Curves*

Table I has been prepared as a convenient summary of all the foregoing material. After a little practice and familiarity with the methods and notation, it and a slide rule and the various "master curves" are all that are needed for the application of these methods.

*Ratios of Gravity to Magnetic Magnitudes*

It is of interest to consider the relative magnitudes of the gravity and magnetic anomalies which might be expected for various shaped bodies on the assumption that density and magnetic contrasts occur at the same boundaries.

TABLE I

| *Form* | *Effect* | *Amplitude Constant** | *Variation Formula* | *Curve No.* | *Fig.* |
|---|---|---|---|---|---|
| Sphere | Gravity | $8.52\sigma R^3/z^2$ | $f_1(x/z)=[1+(x/z)^2]^{-3/2}$ | 1 | 1 |
| Sphere | Magnetism | $8.38\times10^5 I(R/z)^3$ | $f_2(x/z)=[1-x^2/(2z^2)][1+(x/z)^2]^{-5/2}$ | 2 | 1 |
| Horizontal Cylinder | Gravity | $12.77\sigma R^2/z$ | $f_3(x/z)=[1+(x/z)^2]^{-1}$ | 3 | 1 |
| Horizontal Cylinder | Magnetism | $6.28\times10^5 I(R/z)^2$ | $f_4(x/z)=[1-(x/z)^2][1+(x/z)^2]^{-2}$ | 4 | 1 |
| Vertical Cylinder | Gravity | $6.39\sigma R^2/z$ | $f_5(x/z)=[1+(x/z)^2]^{-1/2}$ | 5 | 1 |
| Vertical Cylinder | Magnetism | $3.14\times10^5 I(R/z)^2$ | $f_1(x/z)=[1+(x/z)^2]^{-3/2}$ | 1 | 1 |
| Fault | Gravity | $12.77\sigma t$ | $f_6(x/z)=\frac{1}{2}+(1/\pi)\tan^{-1}(x/z)$ | 6 | 2 |
| Fault | Magnetism | $2\times10^5 It/z$ | $f_7(x/z)=(x/z)[1+(x/z)^2]^{-1}$ | 7 | 1 |
| Vertical Sheet | Gravity | $9.36\sigma t$ | $f_8(x/z)=\log\sqrt{1+(z/x)^2}$ | 8 | 3 |
| Vertical Sheet | Magnetism | $2\times10^5 It/z$ | $f_3(x/z)=[1+(x/z)^2]^{-1}$ | 3 | 1 |
| Horizontal Circular Lamina | Gravity | $2.03\omega\sigma t$ | Solid angle chart | — | 4 |
| Vertical Circular Cylinder | Magnetism | $10^5 I\omega$ | Solid angle chart | — | 4 |
| Two-dimensional slab | Gravity | $4.07\sigma t$ | $\theta$(=subtended angle) | — | — |
| Two-dimensional slab | Magnetism | $2\times10^5 I$ | $\theta_1-\theta_2$ | — | — |

* Values of the amplitude constant, for gravity formulas, give $g$ in milligals when $R$, $z$ and $t$ are in units of kilo-feet and $\sigma$ is the density contrast in c.g.s. units (i.e., grams per cc. or specific gravity). For the magnetic formulas, values give $V$ in gamma for the polarization, $I$, in c.g.s. units (magnetic moment per unit volume). If the susceptibility, $k$, is given and the body is magnetized in the earth's field of $H$ oersteds, (value, in the U. S. around 0.6), then $I=kH$. Since the linear dimensions ($R$, $z$ and $t$) enter the magnetic equations as ratios, their units do not affect the amplitude constants.

For each of the first three shapes considered, the ratio of the magnetic to the gravity amplitude factors[3] is

$$\frac{V}{g}=\frac{I}{\sigma}\cdot\frac{C}{z}; \qquad \frac{zV}{g}=\frac{I}{\sigma}C$$

[3] This relation was first pointed out to the writer by L. H. Bailey.

where $C$ is the ratio of the numerical factors and $z$ is the depth in kilo-feet. From this it is evident that if we had any basis for fixing values for the polarization and density contrast, the ratio $I/\sigma$, together with the ratio of amplitudes of magnetic and gravity anomalies (i.e., $V/g$) would give a means of estimating depth. While such an application is of little practical value because of the uncertainty, particularly of the magnetic polarization contrast, the above expression is of interest in indicating the order of magnitude of the relative magnetic and gravity anomalies which might be expected if they are caused by the same body.

The order of magnitude of density contrasts which might be expected is commonly around 0.25; polarization contrasts for anomalies arising from below the basement surface commonly are in the range .0005 to .0015 (judged from the magnitude of large magnetic anomalies). For actual basement structures where the igneous rock is contrasted with the sediments, the expected contrast is the total polarization and therefore higher—probably, as a rough average, around .0025. Using these figures, we may say that for density and magnetic contrasts within the basement, the ratio $I/\sigma$ may be around .001/0.25 = .004 and for basement structures, $I/\sigma$ may be around .0025/.25 = .01. Using these figures we may construct the following table of ratios of magnetic to gravity anomalies. It is convenient to express the ratio in terms of gamma per milligal for each geometric form (i.e., using the corresponding value of $C$) and for $z = 1$ (i.e., 1000 ft.). For other depths the gamma per milligal value is inversely proportional to the depth.

| *Form* | $C$ (*approx.*) | *Intra-Basement Contrasts* $V/g$ *gamma/mg.* | *Basement Structures* $V/g$ *gamma/mg.* |
|---|---|---|---|
| *Sphere* | $1\times10^5$ | 400 | 1000 |
| *Horizontal Cylinder* | $\frac{1}{2}\times10^5$ | 200 | 500 |
| *Vertical Cylinder (Bottom at* $\infty$*)* | $\frac{1}{2}\times10^5$ | 200 | 500 |

Conversely, if the gravity or magnetic data permit depth estimates, the above relations may be used to give a general idea of the ratio of magnetic to density contrasts. For instance, the huge, roughly circular gravity and magnetic anomaly near Crosbyton, in West Texas, has a magnetic relief of around 2500 gamma and a gravity relief of around 45 mg.[4] The "half width" of the gravity

[4] McLemore, Weaver, and Barton. GEOPHYSICS, Vol. VII, No. 2, p. 179 (April 1942), gives values quite close to those used here, which are from independent gravimeter and magnetometer surveys by Gulf Research & Development Co.

anomaly is around eight miles, by which (from Curve 1 of Fig. 1, for gravity of a sphere) the depth to the center of mass is around ten miles or around 50 kilo-feet. Then

$$C\frac{I}{\sigma} = \frac{zV}{g} = 50 \times \frac{2500}{45} = 2800; \qquad \frac{I}{\sigma} = \frac{2800}{C} = 2800 \times 10^{-5},$$

$$I = 0.028\sigma \text{ c.g.s. units.}$$

If we guess that the density contrast is, say, 0.25, then we get $I = .007$ which is an unusually high value, but perhaps not unreasonable in view of the fact that this feature has an exceptionally large magnetic relief for an anomaly covering a large area. If we consider that the value of $I$ is due to excess magnetite, magnetized in the earth's field, of strength, say, 0.6 oersteds, we can calculate[5] the probable excess magnetite percentage, $P$, for

$$I = kH = 0.3\,PH = 0.3\,P \times 0.6;$$

$$P = \frac{.007}{0.3 \times 0.6} = .04 = 4\% \text{ magnetite (by volume).}$$

*Example of Calculation*

An example of the application of some of the methods outlined above is given by the curve and cross sections of Fig. 5.

The smooth curve is the gravity profile from a very regular circular salt dome minimum. It would be expected that such a curve could be accounted for rather closely by a sphere. From Curve 1 of Fig. 1 (or from the formula for $f_1(x/z)$) it is evident that when the gravity amplitude is one-half the maximum, the width of the gravity curve is 77% of the depth (*i.e.*, $x/z = 0.77$ when $f_1(x/z) = 0.5$). In the above example this "half width" is 13,500 ft., which divided by 0.77 gives 17.5 kilo-feet as the depth, $z$, to the center of the sphere which will give a gravity curve of this width. The radius of the sphere can be calculated from the gravity over the center and the formula for the amplitude factor (*i.e.*, $g_0 = 8.52\sigma R^3/z^2$). With a gravity value of 9.0 mg and a density contrast of, say, 0.25 and the value of $z$ given above, this formula gives a radius of 11.0 kilo-feet. From Curve 1 of Fig. 1, values of $f_1(x/z)$ can be read off as indicated by the first two columns of Table II. Multiplying the $x/z$ values by $z$ (17.5 kilo-feet) gives the values of $x$ in the third column. Multiplying the gravity over the

[5] Nettleton, *op. cit.*, p. 201.

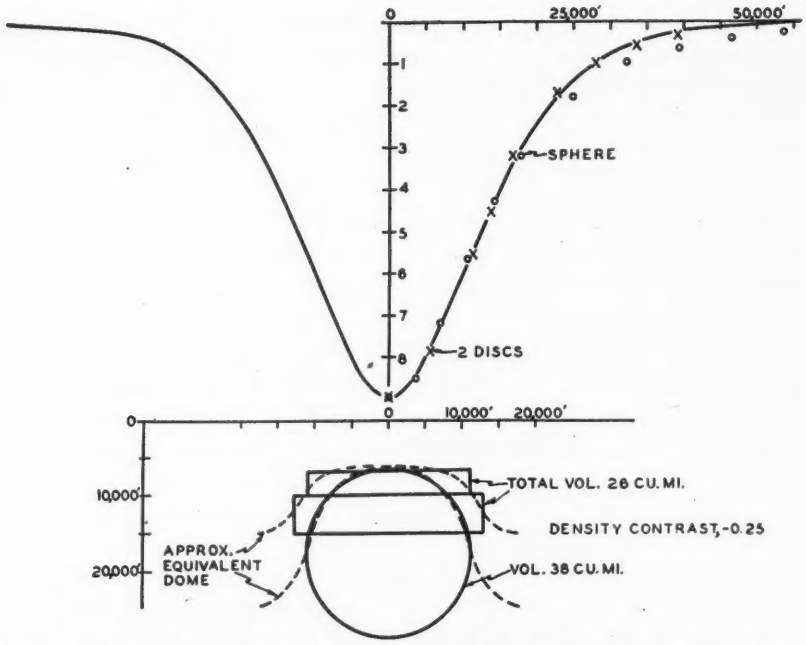



FIG. 5. Gravity effects from a sphere (shown by circles) and from two discs (shown by crosses) calculated to fit observed salt dome minimum (shown by curve).

center (9.0 mg) by the values of $f_1(x/z)$ gives the values of $g$ in the fourth column. The calculated values thus determined are indicated by the circled points on Fig. 5. These fit the observed curve quite closely except far out on the flanks where the calculated points are wider than the observed curve.

TABLE II

*Sphere*

Depth to Center 17.5 Kilo-Ft.

| $x/z$ | $f_1(x/z)$ | $x$ (kilo-ft.) | $g$ (mg) |
|---|---|---|---|
| 0 | 1.000 | 0 | 9.00 |
| 0.2 | .945 | 3.5 | 8.52 |
| 0.4 | .800 | 7.0 | 7.20 |
| 0.6 | .630 | 10.5 | 5.67 |
| 0.8 | .475 | 14.0 | 4.28 |
| 1.0 | .355 | 17.5 | 3.20 |
| 1.4 | .200 | 24.5 | 1.80 |
| 1.8 | .111 | 31.5 | 1.00 |
| 2.2 | .070 | 38.5 | 0.63 |
| 2.6 | .048 | 45.5 | 0.42 |
| 3.0 | .032 | 52.5 | 0.29 |

From the depth to the center and the radius of the sphere thus determined, it is evident that the depth to the mother salt layer to accommodate such a dome would have to be of the order of 25,000 ft.

Now suppose that this same anomaly had been observed in an area where, from geological considerations, the depth to the salt could not be as great as 25,000 ft. Let us say, for instance, that the geologist has restricted the geophysicist to a depth of 15,000 ft. It is evident that we will have to guess at a shallower and wider salt mass to account for the gravity anomaly. The gravity effect of such a mass can be readily calculated by the use of solid angles. For instance, suppose that we assume a dome built up of two discs, the first having its bottom at 15,000 ft. and a thickness of 5000 ft. After a little guessing based on the width of the observed gravity curve we set a radius for this disc of 13,000 ft. Its mean depth $z$ is 12,500 ft. and $z/R=.962$. On the solid angle chart, Fig. 4, we read along a vertical line at the horizontal coordinate $z/R=.962$ values for $x/z$ at each solid angle

TABLE III

*Lower Disc*

$z=12500'$ $R=13000'$
$z/R=.965$ $\omega_0=1.95$
$t=5000'$ $\sigma=0.25$
$g=2\times\omega\times5\times0.25=2.5\omega$

| $\omega$ | $x/z$ | $x$ (kilo-ft.) | $g$ (mg) |
|---|---|---|---|
| 1.95 | 0 | 0 | 4.87 |
| 1.5 | .73 | 9.1 | 3.75 |
| 1.0 | 1.17 | 14.6 | 2.50 |
| 0.7 | 1.50 | 18.7 | 1.75 |
| 0.5 | 1.74 | 21.8 | 1.25 |
| 0.4 | 1.90 | 23.7 | 1.00 |
| 0.3 | 2.14 | 26.8 | .75 |
| 0.2 | 2.46 | 30.8 | .50 |
| 0.1 | 3.20 | 40.0 | .25 |
| 0.05 | 4.05 | 50.6 | .12 |

$\omega_0$= value of solid angle at point over center of disc (where $x=0$), which can be read from insert curves on solid angle chart.

curve and obtain the values given in the first two volumns of Table III below. Multiplying the $x/z$ values by the value of $z$ (12.5 kilo-feet) we get the $x$ values given in the third column. Multiplying the solid angle values by 2.5 ($2.5=2^*\times t$ in kilo-feet $\times$ the density contrast, taken as 0.25) gives the gravity values in Column 4 from which a calculated gravity curve can be plotted.

* Strictly 2.03, but the difference from 2 can be ignored for approximate calculations of this kind.

TABLE IV

*Upper Disc*

$z = 8300'$ $R = 11000'$
$z/R = .755$ $\omega_0 = 2.52$
$t = 3280'$ $\sigma = 0.25$
$g = 2 \times \omega \times 3.28 \times 0.25 = 1.64\omega$

| $\omega$ | $x/z$ | $x$ (kilo-ft.) | $g$ (mg) |
|---|---|---|---|
| 2.50 | 0 | 0 | 4.10 |
| 2.0 | .80 | 6.6 | 3.28 |
| 1.5 | 1.24 | 10.3 | 2.46 |
| 1.0 | 1.63 | 13.5 | 1.64 |
| 0.7 | 1.95 | 16.2 | 1.15 |
| 0.5 | 2.20 | 18.3 | .82 |
| 0.4 | 2.38 | 19.8 | .65 |
| 0.3 | 2.68 | 21.8 | .50 |
| 0.2 | 3.00 | 24.9 | .33 |
| 0.1 | 3.81 | 31.6 | .17 |
| 0.05 | 4.80 | 39.8 | .08 |

From the difference between the central value given by this disc (4.87 mg.) and the total gravity required (9.0 mg) it is evident that the second and shallower disc must have a gravity effect at its center of 4.13 mg. After a little guessing and preliminary calculating the second disc indicated by the calculations of Table IV below was arrived at. A second curve is plotted from the gravity and distance values of the last two columns of this table. Adding the two curves together at arbitrary distance values gives the calculated total effect of the two discs indicated by the crosses on Fig. 5. This calculated effect, on the whole, fits the observed curve somewhat better than does the sphere, although the differences probably are not sufficient to serve as a basis for deciding that the actual salt mass has one shape rather than the other.

The above example also serves to show the ambiguity in the possible source of a given gravity curve where no other control is available and illustrates why approximate methods such as have been outlined here are sufficiently accurate to answer most questions regarding possible sources of anomalies when other control is not available.

In conclusion the writer wishes to express his thanks to several members of the staff of the gravity section of the geophysical division of the Gulf Research & Development Company who have contributed in various ways to this material, particularly to Mr. T. A. Elkins who has checked all the mathematical parts, and to Drs. P. D. Foote and E. A. Eckhardt for permission to publish this paper.

# THE PRODUCTION OF ELASTIC WAVES BY EXPLOSION PRESSURES. II. RESULTS OF OBSERVATIONS NEAR AN EXPLODING CHARGE*

JOSEPH A. SHARPE†

ABSTRACT

A high fidelity recording system has been used to observe the elastic wave motion at vertical separations from an exploding charge ranging from 15 to 300 feet. The motion near the charge has a predominant frequency of about 1000 cps for rigid material and a duration of a few milliseconds. The motion becomes increasingly complex and low frequency components become dominant as the point of observation recedes from the source.

A secondary wave which may be a bound wave associated with the fluid in the drill hole was observed.

## INTRODUCTION

The observations to be described in this paper were made primarily for the purpose of determining the form of the elastic wave motion in the Earth near an exploding charge, and the nature of its departure from some of the predictions of the theory presented in Part I. However, these observations also offer a qualitative illustration of dispersive propagation of elastic waves, and suggest the existence of a bound wave of a type not previously described in geophysical literature.

For comparison with the results of the observations, Equation 13 of Part I has been utilized to compute, with the aid of Duhamel's integral, the particle velocity which results when a pressure pulse is applied to the interior surface of a cavity of diameter 2.54 feet within a medium of compressional wave velocity 8500 feet per second and Poisson's ratio of 0.25. The pressure pulse was chosen to have a total duration of 0.5 milliseconds, composed of a buildup of the form $1-\cos \omega_1 t$ lasting for 0.1 milliseconds, and a decay of the form $1+\cos \omega_2 t$ lasting 0.4 millisecond. The duration and form of the pressure pulse selected is consistent with the results of observations which we have made of the pressure wave in water caused by the detonation of an explosive charge.

* Presented at the 1941 Spring meeting, Houston. Part I appeared in the April number of this Journal.

† Joint Geophysical Laboratory of the Stanolind Oil and Gas Company and the Western Geophysical Company.

Fig. 1 illustrates the pressure pulse, and the particle velocity in the resulting wave motion. It is to be noted that the wave motion is of very simple form and short duration. Although, of course, all frequencies are present in the motion, frequencies of 1200–2500 cps. appear to predominate.

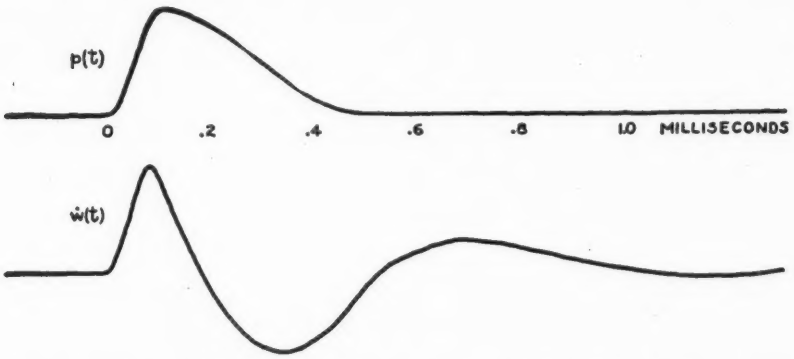



FIG. 1. Calculated particle velocity of wave motion in an elastic medium, $\dot{w}(t)$, resulting from application of a pressure pulse with a duration of 0.5 milliseconds to the interior surface of a spherical cavity in an elastic medium. Diameter of cavity is 2.54 feet, compressional wave velocity is 8500 feet per second, and Poisson's ratio is 0.25.

## INSTRUMENTS AND PROCEDURE

In order to accomplish high fidelity recording of the motion near an exploding charge, instruments of special design were required, as described in the following paragraphs.

The pickup was of the dynamic type, operated at a natural frequency of 20 cps and with low damping. Extreme care was taken to avoid non-linear distortion and parasitic modes of vibration. Features of the construction were high rigidity of the case and of all moving members, the use of connected dual coil forms moving in dual gaps, and the employment of symmetric double-diaphragm suspension of the coils in order to insure freedom from response to the horizontal and rotational components of motion. Shaking table and impedance tests indicated that this pickup was completely free from parasitics at all frequencies to 3000 cps, which was as far as the tests were carried.

A conventional RC coupled amplifier was used. Provision was made for the insertion of an electrical integration network, as a result of which recordings could be made which represented either the displacement in the wave motion, or the particle velocity, at will.

The recorder consisted of a 3 inch cathode ray oscilloscope equipped with an actinic screen tube, and a high speed moving film camera. This camera employed an F1.5 lens, 2 inches in diameter, to focus the face of the oscilloscope on 35 mm film wrapped around a continuously rotating drum 18 inches in circumference. Between the lens and the drum there was a cylindrical rotary shutter operated by the shaft driving the drum, which, upon operation of the shutter release, opened the shutter just after the joint in the film had passed, closed a contact which initiated the phenomenon to be studied, and after the drum had made a complete revolution, closed the shutter. In order to secure recordings with proper resolution along the time axis, it was necessary to employ a speed of film travel of 150 inches per second, which required the use of Ultraspeed film, postsensitized by mercury, to secure a trace of readable density.

The charge was detonated by a battery, the firing circuit being closed by the camera shutter contactor. A conventional inductive time-break circuit was used to superimpose a time break on the trace. Clean voltage application and bridge wire rupture breaks were always visible on the trace.

In order to secure a timing trace on the record, it was arranged that immediately after recording a shot a switch would be thrown which would deflect the trace to the edge of the film, connect a 1000 cps oscillator to the oscilloscope, and expose the film a second time. The accuracy of this scheme of timing depended upon the constancy of the speed of rotation of the drum, but it appears, from the evidence of repeat shots, that times determined from the records were never in error from this source by more than 0.1 millisecond.

The complete system (pickup, amplifier and recorder) was calibrated in absolute units by means of a constant velocity electrodynamic drive shaking table. The amplifier response was chosen such as to make oscilloscope trace displacements proportional to ground velocity or ground displacement within 1 db over the ranges of 100–3000 cps and 75–3000 cps, respectively. The magnifications at maximum amplifier gain were determined to be 296 cm trace displacement on the film per cm per second ground velocity, and 550,000 cm trace displacement per cm ground displacement.

At the site utilized for the observations, a $6\frac{1}{2}$ inch hole was drilled to a depth of 310 feet, and three other holes spaced on the circumference of a circle of 5 foot radius about the first hole were drilled to depths of 8, 40 and 56 feet, respectively, as shown in section and plan

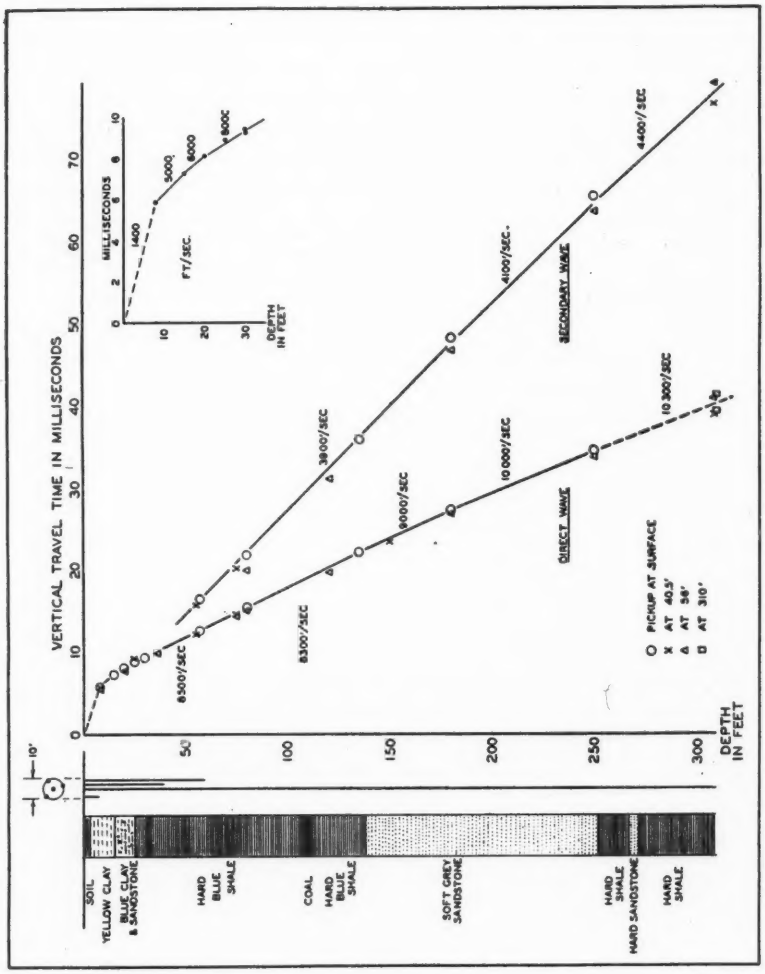



FIG. 2. Driller's log at the site of the experiments, section and plan of shot and receptor holes, and vertical travel time curves of direct and secondary waves. Detail of shallow portion of direct wave vertical time curve shown in upper right.

in Fig. 2. After penetrating 15 feet of surface soil and yellow clay the holes passed through 10 feet of blue clay with sandstone breaks to go into very competent material (hard blue shale of Pennsylvanian age) at a depth of 25 feet. The material between 25 feet and the bottom of the hole was quite homogeneous, being composed mainly of thick layers of hard shale and sandstone, as can be seen on the driller's log shown in Fig. 2.

The pickup was first planted very solidly in the bottom of the 310 foot hole, and shots of $\frac{1}{8}$ pound of 60% gelatine dynamite were made in the bottoms of the other three holes. The pickup was then planted in the bottom of the 56 foot hole, and shots of the same size were taken at intervals in the 310 foot hole, and in the bottoms of the other two holes. Proceeding in this manner, the pickup was finally brought to the surface, and shots recorded at intervals in the four holes.

Special precautions were employed to prevent the possibility of transmission of vibration to the pickup along either the pickup cable or the shot fire cable. The cables were centered in the holes, and supported by airplane shock absorber cord from tripods at the surface. In addition, several inches of slack was taken in the cable just above the pickup, and bridged with shock absorber cord.

Travel-times read from the various recordings served to provide the time-depth curve in Fig. 2 which is labelled "direct wave." Interval times between various pickup and shot positions as well as the times to the surface were used in establishing this curve, as is indicated by the designation of the points. In the upper right hand portion of the figure the shallow portion of the time-depth curve has been reproduced at an enlarged scale. The curve in Fig. 2 labelled "secondary wave" will be discussed later.

It is to be noted in Fig. 2 that the thickness of the low velocity zone is not more than 8 feet, and that the velocity increases rapidly and more or less continuously below this depth, from 5000 feet per second to about 8000 feet per second, after which it slowly increases to 10,300 feet per second.

## RESULTS OF THE OBSERVATIONS

All of the recordings were made with the same charge size, $\frac{1}{8}$ pound. A small, constant charge was chosen for two reasons, to avoid complex motions due to fracturing, and to ensure that the character of the motion would repeat in successive shots at the same depth, by avoiding the formation of a constantly enlarging cavity.

vertical time curve shown in upper right.

Displacement as well as velocity recording was provided for, with the idea that particle displacement in wave motion is somewhat easier to visualize than particle velocity, and with the possibility in mind that displacement recording might give simpler wave forms and a more convenient distribution of recorded amplitudes. However, it turned out that the recordings confined themselves to the width of the film better when velocity recording was used, and consequently all but one of the recordings to be reproduced here represent the particle velocity in the wave motion.

The illustrations of ground motion appearing in this section were traced from the original recordings for the sake of clarity of reproduction. The length of the line at the bottom of each figure corresponds to a time interval of 0.01 second.

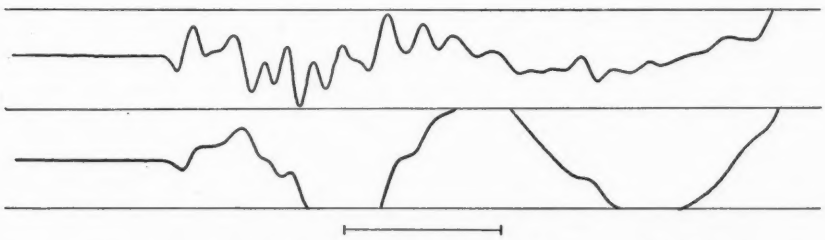


FIG. 3. Ground velocity (top trace) and displacement observed with the pickup at a depth of 310 feet and shot at a depth of 39 feet. Predominant frequencies are 400–600 cps and 50–70 cps. Length of line corresponds to distance of film travel in 0.01 second.

Fig. 3 shows the ground velocity (top trace), and the displacement which were observed with the pickup located at 310 feet, as a result of shooting at 39 feet. Note that the motion is complex and that the high frequency component seen particularly on the velocity recording retains appreciable amplitude for about 25 milliseconds. The predominant frequencies present in the motion appear to be 400–600 cps and 50–70 cps. The low frequency motion is seen to be continuously increasing with time. It is not known for how many more cycles this motion would continue.

Fig. 4 shows the motion at 40 feet, resulting from shots at 8, 25, 55, 150 and 309 feet. Several observations of interest are illustrated by these records. The motion resulting from the shot at 55 feet is relatively complex, compared to the predictions of theory as exemplified by Fig. 1, and the predominant frequency is very high, of the order of 1000 cps, which is of the order of the frequency predicted by theory.

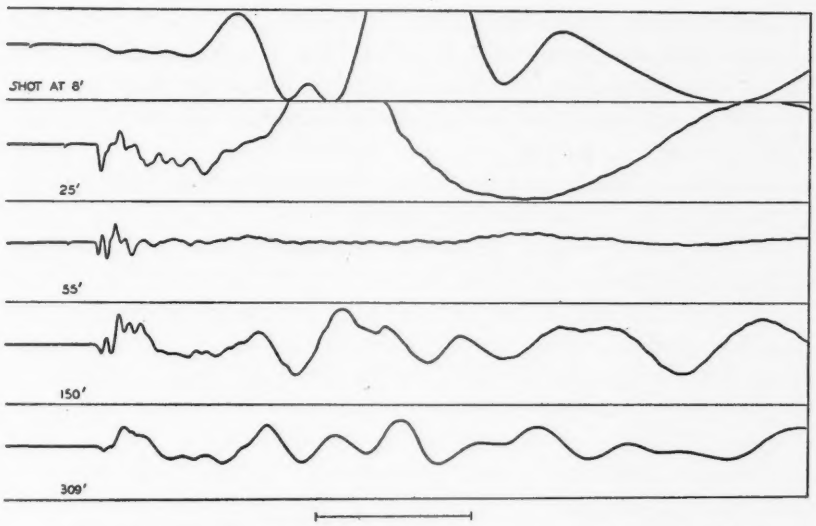



FIG. 4. Ground velocity observed with the pickup at 40 feet, which resulted from shooting at 8, 25, 55, 150, and 309 feet, respectively.

As the shot is taken deeper the high frequencies gradually attenuate and the lower frequencids, of the order of 100–200 cps, become dominant. The shot at 25 feet, which is the same distance from the pickup as the shot at 55 feet, has a somewhat different appearance initially, although the predominant frequency is about the same, and in the later portion of the record there is a strong development of very low

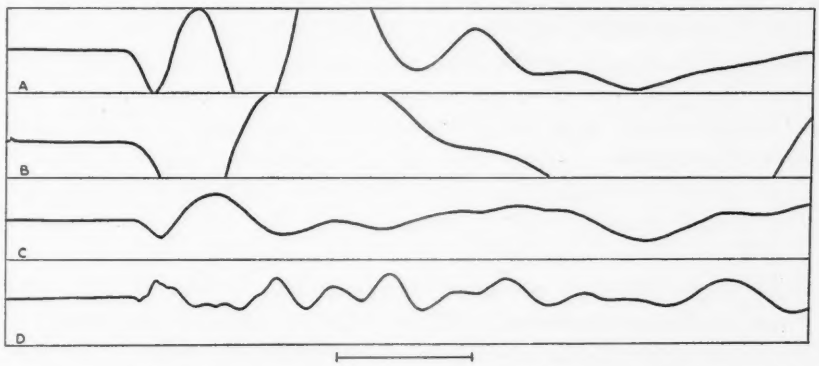



FIG. 5. Record A. Pickup at surface, shot at 30 feet in hard blue shale. Record B. Pickup at surface, shot at 20 feet in clay. Record C. Pickup at surface, shot at 250 feet in sandstone. Record D. Pickup at 40 feet, shot at 309 feet in hard shale.

frequency motion of about 35 cps. The high frequencies are completely lost in the recording of the shot made at 8 feet, probably due both to the generation of less high frequency, and to the added attenuation of high frequencies in transmission through the clay between depths of 8 and 25 feet.

Records similar to those shown in Fig. 4 were made with the pickup located at 56 feet, with similar results.

In all of the records shown in Fig. 5 the pickup was at the surface, with the exception of Record D, for which it was at 40 feet. Records A and B, in which the shots were placed at 30 feet in hard blue shale and at 20 feet in clay, respectively, demonstrate the effect of the material in which the shot was fired upon the frequency of the motion. It is to be noted that the frequency in the early motion is about 70 cps for the shot fired at 20 feet, and double that for the shot fired at 30 feet.

Record C, shot at 250 feet, and Record A illustrate the degree of attenuation of frequencies of the order of 150 cps as a result of transmission through an additional 220 feet of material. Despite the fact that the shot at 250 feet was fired in a more rigid material, as indicated by the velocity of propagation, there was still sufficient attenuation to make the period of the motion which resulted from this shot slightly longer than that which resulted from the shot fired at 30 feet.

Records D and C of Fig. 5 illustrate the extreme attenuation of high frequencies which occurs during transmission through the low velocity zone. For Record D, for which the shot is at 309 feet and the pickup at 40 feet, the transmission path is 269 feet long, but does not include the 40 feet of material near the surface. For Record C the transmission path is slightly shorter (250 feet) and includes the material adjacent to the surface. It is to be noted that frequencies ranging from 250–1000 cps have completely disappeared from the motion which traversed the shallow zone, and that, in addition, an extreme form of distortion appears to have occurred, which amounts to a complete reversal of phase of the low frequency components during the first 20 milliseconds of the recordings.

The trace amplitudes of the initial motion of all velocity recordings were scaled off and converted to ground velocities. The ground velocities ranged from values of the order of 0.001 cm per second at the larger intervals between shot and pickup to values of the order of 0.2 cm per second at the short intervals. Since the individual points scattered badly, no tabulation of them will be presented here. However, a plot of the logarithm of the product of the interval and the

velocity as a function of the interval definitely verifies the dissipation of the high frequencies that is noted qualitatively in examination of the recordings, and provides a rough estimate of the magnitude of the attenuation due to dissipation, which seems to be about 6 db per 50 feet for the material below the low velocity zone.

The records were carefully examined for evidence of waves reflected from velocity discontinuities at the free surface and between strata, but none was observed. The recognition of reflections would have been greatly facilitated if the shots had been taken at much closer intervals. However, in the course of the search for reflected

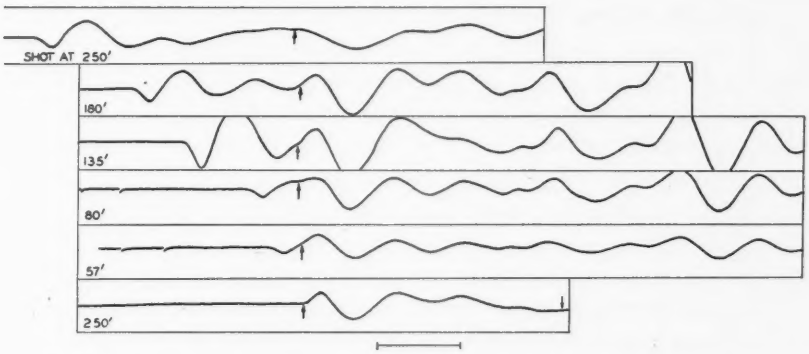



FIG. 6. Pickup at surface. Records traced side by side without reference to position of time break in order to emphasize correlation of the form of the motion after the event indicated by the arrow. Bottom record is an inverted tracing of the early part of the 250 foot record.

waves, a secondary wave which is definitely not a reflection was recognized.

This wave is illustrated in the first five of the group of records reproduced in Fig. 6. These records were made with the pickup at the surface, and shots fired at 250, 180, 135, 80 and 57 feet. The records have been placed side by side without reference to the position of the time break, in order to emphasize the correlation in the form of the motion. The apparent arrival of the secondary wave is indicated by the arrows, and it is to be noted that the correlation between records is excellent for as much as 60 milliseconds after the arrival of the secondary. The same wave was observed when the pickup was located at 40 and 56 feet, for shots made deeper than the pickup. The time-depth curve for the secondary wave which is derived from these three

sets of observations is shown in Fig. 2. The curve establishes about 4000 feet per second as the velocity of propagation of this wave.

The record made by the shot at 250 feet has been reproduced, inverted in phase, as the last trace in Fig. 6. The close similarity between this trace and the remainder of the records strongly suggests that the secondary, whatever its origin, has the same form as the primary motion, but with its phase inverted, and has about the same amplitude as the primary motion.

To summarize the characteristics of this secondary wave: the ratio of its velocity to that of the primary wave is about 1:2.3; and it apparently has the same form and amplitude as the low frequency component of the primary wave, but is reversed in phase.

In seeking to account for this secondary wave, one is at first inclined to call it a shear wave. However, shear waves to my knowledge have never been observed as a result of firing explosives in a drill hole, and, additionally, the ratio of the velocity of this wave to that of the compressional wave demands a Poisson's ratio of about 0.40 if it is a shear wave, which seems excessive for the very competent material involved. I am more inclined to believe that it is the "thickwalled tube wave" which was studied analytically by Lamb.[1] The thickwalled tube wave is a bound wave, *i.e.*, its amplitude decreases exponentially with distance away from the wall of the drill hole. Its characteristics are as follows: when a wave of a wavelength much greater than the diameter of the bore is propagated down the liquid which fills a thickwalled tube, the velocity of propagation will not be that characteristic of the liquid, but will be less, by an amount depending upon the rigidity and velocity of sound in the material of the wall, in accordance with the approximate formula

$$(v_T)^{-2} \simeq (\rho_L v_L^2)^{-1} + (\rho v^2/3)^{-1}$$

in which $v_T$ is the velocity of the tube wave, $\rho_L$ and $\rho$ are the densities of the liquid and the medium, respectively, and $v_L$ and $v$ are the corresponding velocities, and Poisson's ratio has been taken as 0.25. Using this formula with the velocity data at hand one computes the density of the formations to be 2.0, which is probably too small by at least 10%.

[1] Lamb. Manchester Memoirs, Vol. 42, No. 9 (1898).

Dr. S. S. West, of the Laboratory with which the writer is associated, first recognized the existence of the thickwalled tube wave in the Earth in the course of an unrelated investigation.

## SUMMARY AND CONCLUSIONS

When a shot is fired in high velocity, competent material, the motion near the source is predominantly of very high frequency, of the order of 1000 cps, of short duration, of the order of a few milliseconds, and of fairly simple form. The observed frequency of the predominant components is consistent with the prediction of the theory based on a simplified model, but the form of the motion is more complex and the duration of the motion is longer than to be expected from the theory.

When the shot is fired in a medium of lower velocity and lesser competence the predominant frequency in the motion near the source is lowered, in accordance with the prediction of theory.

As the point of observation is taken further and further from the source, the wave motion becomes more and more complex, and the motion appears as a *train* of waves whose predominant frequency is dictated by the degree of dissipation at the distance of observation.

Dissipation of the very high frequency components of the motion is rapid, and even in the competent material dissipation of frequencies as low as 150 cps in transmission through a distance of 200 feet is observable. The dissipation of the high frequencies, from 250 cps up, is extremely large for transmission through the low velocity zone.

A low frequency secondary wave of amplitude comparable to that of the primary wave is observed. It seems probable that this is a bound wave, associated with the drill hole and its contained fluid, rather than a body wave. Its importance lies in the fact that it may be a factor to be contended with in any effort to observe the interval velocity within formations traversed by a bore hole when the separation between source and receiver is small.

This work suggests that the true ground motion which results from the detonation of a charge of explosive in a drill hole is not a simple pulse, but a relatively long train of almost sinusoidal waves, which lengthens in both period and in number of cycles with increasing distance from the source. Consequently, the concept of a reflection seismic record as being the instrumental transient response to a series of "bumps" of simple form and short duration may be erroneous.

I wish to express my appreciation to the officers of the Stanolind Oil and Gas Company and the Western Geophysical Company for permission to publish this paper, and to Messrs. Joseph D. Eisler and A. C. Reid for their assistance.

# PATENTS*

## ELECTRICAL PROSPECTING

*U.S. No. 2,274,903.* S. Krasnow and J. M. S. Kaufman. Iss. 3/3/42. App. 2/6/37.

*Electrical Prospecting Apparatus.* An earth resistivity apparatus which embodies a leakage guard circuit and a standardizing circuit.

*U.S. No. 2,276,974.* See under "Seismograph Prospecting."

*U.S. No. 2,277,701.* F. W. Lee. Iss. 3/31/42. App. 9/12/34 and 4/8/38.

*Electric Impedisivity or Resistivity Measuring.* A method of electrical surveying in which the current supplied to the ground varies with the electrode spacing so that the potentiometer scale is made direct-reading.

*U.S. No. 2,278,506.* T. Zuschlag. Iss. 4/7/42. App. 10/4/39. Assign. Lundberg Exploration S. A.

*Apparatus for Geophysical Prospecting.* An apparatus for making repeated electrical transient observations in which the ground potential is measured during any portion of the transient by mechanical and electronic switching.

## GEOCHEMICAL PROSPECTING

*U.S. No. 2,266,556.* W. A. Kelly. Iss. 12/16/41. App. 8/31/38.

*Method of Locating Oil Deposits.* Geochemical prospecting by drilling holes, inserting containers of gas-absorbing material and later analyzing the gas absorbed in each hole.

*U.S. No. 2,278,929.* L. Horvitz. Iss. 4/7/42. App. 11/18/39. Assign. E. E. Rosaire.

*Geochemical Prospecting.* A method of soil analysis in which soil samples or well cuttings are treated with acids to determine the free metal and hydrogen present.

*U.S. No. Re. 22081.* J. C. Campbell. Reiss. 4/28/42. App. 1/7/41, 3/26/41. Assign. R. H. Fash.

*Method of Determining the Petroleum Oil Content of Earth Samples.* Dissolving the oil from samples with a solvent and comparing the fluorescence of the solution with standard solutions of known concentration.

## GRAVIMETRIC PROSPECTING

*U.S. No. 2,277,505.* C. H. Barker and K. Q. Robert. Iss. 3/24/42. App. 2/24/40. Assign. Socony-Vacuum Oil Co.

*Carrying Device for Geophysical Instrument.* A truck mounting for a gravity meter which affords protection in transit and makes it unnecessary to unload the instrument from the truck when taking a reading.

* Abstracts by O. F. Ritzmann, Gulf Research & Development Co.

*U.S. No. 2,277,509.* D. H. Clewell. Iss. 3/24/42. App. 2/21/40. Assign. Socony-Vacuum Oil Co.

*Gravity Meter.* A damping means for a gravity meter obtained by discharging a condenser through a coil near the moving system, thus imparting a momentary impulse.

*U.S. No. 2,279,261.* J. M. Crawford and H. R. Prescott. Iss. 4/7/42. App. 10/25/39. Assign. Continental Oil Co.

*Torsion Gravimeter.* A quartz torsion gravimeter of the Mott-Smith type, but using two torsion fibers connected by a labilizer fiber in such a way that the calibration is linear over a wide range of gravity.

*U.S. No. 2,281,001.* D. H. Clewell. Iss. 4/28/42. App. 5/24/40. Assign. Socony-Vacuum Oil Co.

*Gravity Meter.* A gravity meter of the unbalanced horizontal beam type, having a small movable mass suspended from the main mass by an elastic pendulum and making null readings by adjusting the horizontal position of the small mass.

## SEISMOGRAPH PROSPECTING

*U.S. No. 2,272,201.* H. Hoover, Jr. Iss. 2/10/42. App. 7/28/39. Assign. Consolidated Engineering Corp.

*Method and Apparatus for Signaling.* A method of correcting for dispersion and phase distortion in seismic prospecting by using a corrective network which may be varied with time.

*U.S. No. 2,275,735.* R. T. Cloud. Iss. 3/10/42. App. 6/23/39. Assign. Stanolind Oil and Gas Co.

*Method and Apparatus for Determining Distances of Elastic Discontinuities.* Continuous wave seismic investigations in which a continuously varying frequency generator is used and time comparison is made between the waves picked up at adjacent and distant points.

*U.S. No. 2,276,306.* H. Hoover, Jr. and H. C. Schaeffer. Iss. 3/17/42. App. 7/26/39. Assign. Consolidated Engineering Corp.

*System for Making Weathering Corrections.* Taking vertical shots with a number of geophones in a shallow hole and from the travel times determining the thickness and velocity of the weathered layer.

*U.S. No. 2,276,335.* R. A. Peterson. Iss. 3/17/42. App. 7/24/39. Assign. Consolidated Engineering Corp.

*Method of Making Weathering Corrections.* Placing a number of geophones in a shallow vertical hole and a shot at the bottom of a similar hole some horizontal distance away, and from the travel times determining the thickness and velocity of the weathered layer.

*U.S. No. 2,276,708.* R. D. Wyckoff. Iss. 3/17/42. App. 10/2/40. Assign. Gulf Research and Development Co.

*Seismograph Amplifier.* A seismograph amplifier controlled by an expander and adapted to record first arrivals at high amplification by having the expander controlled tube by-passed by an auxiliary high amplification tube which is caused to become inoperative after the first arrival.

*U.S. No. 2,276,709.* R. D. Wyckoff. Iss. 3/17/42. App. 10/14/40. Assign. Gulf Research and Development Co.

*Apparatus for and Method of Seismograph Prospecting.* An automatically controlled expander for a seismograph amplifier in which the expansion is momentarily arrested by the arrival of a large impulse.

*U.S. No. 2,276,974.* G. M. Howard. Iss. 3/17/42. App. 6/14/40.

*Method of and Means for Determining the Velocity of Propagation of Waves through Subsurface Formations.* A method of recording electric or seismic ground transients in which the pick-up modulates the frequency of an oscillator and the change or the difference in frequency between two pick-up points recorded.

*U.S. No. 2,279,191.* J. L. Adler. Iss. 4/7/42. App. 8/13/40. Assign. F. M. Kannenstine.

*Method and Apparatus for Seismic Surveying.* A method of seismic recording in which each channel passes and records one band of a series of predetermined frequency bands covering the seismic spectrum.

*U.S. No. 2,281,751.* R. T. Cloud. Iss. 5/5/42. App. 11/10/39. Assign. Stanolind Oil and Gas Co.

*Seismic Wave Generation Apparatus.* An apparatus for use as a source of continuous seismic waves consisting of a hydromechanical system for exerting sinusoidal hydrostatic pressure in a shallow bore hole.

*U.S. No. 2,281,949.* O. F. Ritzmann. Iss. 5/5/42. App. 12/14/38. Assign. Gulf Research & Development Co.

*Apparatus for Seismograph Prospecting.* A method of automatically controlling the sensitivity of seimograph amplifiers by means of a control channel having its detector located closer to the shot than the channel being controlled.

*U.S. No. 2,283,200.* J. W. Flude. Iss. 5/19/42. App. 9/16/39.

*Method and Apparatus for Subsurface Mining.* A method of seismic surveying in water covered areas in which all operations are carried on from a single boat and detectors are towed into position.

## WELL LOGGING AND SURVEYING

*U.S. No. 2,266,623.* S. W. Gurasich. Iss. 12/16/41. App. 9/14/38. Assign. Sperry-Sun Well Surveying Co.

*Method of Surveying Boreholes and Locating Tools Therein.* A directional well-surveying instrument and a method of using it as a check on an oriented drill stem when placing whipstocks or other tools.

*U.S. No. 2,274,248.* S. A. Scherbatskoy and J. Neufeld. Iss. 2/24/42. App. 5/7/37. Assign. Well Surveys, Inc.

*Well Surveying Method.* A well logging method which measures thermal absorptivity by lowering a source of heat in the well and comparing temperatures measured at two points around the heat source.

*U.S. No. 2,275,456.* J. Neufeld. Iss. 3/10/42. App. 6/7/39. Assign. Well Surveys, Inc.

*Method and Apparatus for Radioactive Investigation of Drill Holes.* A method of gamma ray well logging which uses a high pressure ionization chamber and d-c amplifier to detect radiations.

*U.S. No. 2,275,736.* R. T. Cloud. Iss. 3/10/42. App. 2/14/40. Assign. Stanolind Oil and Gas Co.

*Seismic Wave Velocity Well Logging.* A method of seismic well logging using a continuous wave generator and a detector some distance away in the well, compensating for the time delay of various waves received and from this determining the seismic velocity of the adjacent formations.

*U.S. No. 2,275,747.* R. E. Fearon. Iss. 3/10/42. App. 12/27/39. Assign. Well Surveys, Inc.

*Well Survey Method and Apparatus.* A method of recording ionization current in gamma ray well logging which permits speeding up the measurements by observing a combination of resistor current and rate of change of resistor current.

*U.S. No. 2,275,748.* R. E. Fearon. Iss. 3/10/42. App. 3/28/40. Assign. Well Surveys, Inc.

*Well Survey Method and Apparatus.* A method of gamma ray or neutron well logging which uses an interrupted source of excitation and selective amplification of the frequency of interruption in the detecting system.

*U.S. No. 2,281,301.* C. P. Walker. Iss. 4/28/42. App. 11/14/40.

*Means for Determining the Location of Obstructions in Wells.* Accentuating reflections in an acoustic echo fluid level measuring device by using a resonator consisting of a cavity with a short, small diameter, connecting pipe.

*U.S. No. 2,281,766.* P. F. Hawley. Iss. 5/5/42. App. 12/29/39. Assign. Stanolind Oil and Gas Co.

*Logging of Permeable Formations Traversed by Wells.* A method of logging the permeability potential of formations in a well by using one electrode centrally located in the hole and another electrode spaced horizontally from it.

*U.S. No. 2,281,960.* V. V. Vacquier. Iss. 5/5/42. App. 7/26/39. Assign. Gulf Research & Development Co.

*Apparatus for Logging Bores.* Logging a well by running a stylus along the walls of the well and recording at various depths the vibrations of the stylus either electrically or optically.

*U.S. No. 2,283,429.* G. H. Ennis. Iss. 5/19/42. App. 12/17/34. Assign. One-half to R. V. Funk.

*Method of and Apparatus for Determining the Location of Water Strata in Wells.* A method of locating the point of fluid entrance in a well by running an instrument in the hole which measures either optical or acoustic properties of the medium in the hole.

*U.S. No. 2,283,477.* C. P. Walker. Iss. 5/19/42. App. 10/26/37 and 4/19/39.

*Method of Determining Location of Liquid Level in Wells.* A method of determining when a pumping well is pumped down, by recording the sound waves in the annular well space at the well head; an abrupt change or broken wave form denoting entry of free gas into the pump.

## MISCELLANEOUS

*U.S. No. 2,275,316.* O. F. Ritzmann. Iss. 3/4/42. App. 6/26/41. Assign. Gulf Research & Development Co.

*Apparatus for Sending and Recording Time Impulses.* A method of obtaining clear shot-moment time breaks in seismic prospecting by the use of rectifiers to suppress the impulse from current build-up in the cap and pass the impulse from the break.

*U.S. No. 2,276,423.* D. Silverman. Iss. 3/17/42. App. 8/31/39. Assign. Stanolind Oil and Gas Co.

*Recording System.* A system of multi-channel recording using pen type recording elements spaced or staggered so that traces may be placed close together and compensating electrically for the apparent time shift caused by the space misalignment.

*U.S. No. 2,276,565.* M. G. Crosby. Iss. 3/17/42. App. 5/23/39. Assign. Radio Corp. of America.

*Limiting Amplifier.* An amplifier output limiter consisting of a double triode and wave shaping circuit.

*U.S. No. 2,277,110.* C. H. Johnson. Iss. 3/24/42. App. 12/31/38.

*Method of Determining Where Pipe is Stuck in a Well.* Exciting a mechanical vibration in the pipe and making a record of the reflected and transmitted vibrations picked up by a detector in contact with the pipe in order to determine from these where pipe is stuck.

*U.S. No. 2,277,521.* M. D. McCarty. Iss. 3/24/42. App. 10/29/38. Assign. Socony-Vacuum Oil Co.

*Timing Device.* An a-c driven, vibrating reed, light beam chopper for timing oscillograph records.

*U.S. No. 2,277,756.* D. G. C. Hare. Iss. 3/31/42. App. 6/26/40. Assign. The Texas Co.

*Method and Apparatus for Measuring Thickness.* A method of measuring thickness of pipe, etc., when having access to one side only, by using penetrating radiation and measuring scattering.

*U.S. No. 2,279,124.* W. H. Mayne. Iss. 4/7/42. App. 6/24/41. Assign. O. S. Petty.

*Oscillograph.* A multiple string oscillograph having pole pieces designed to reduce tangling of the strings.

*U.S. No. 2,280,075.* J. T. Hayward. Iss. 4/21/42. App. 2/23/38.

*Detection of Gas in Drilling Fluids.* A method of detecting gas in drilling mud by measuring the change in volume of a sample when subjected to reduced pressure.

*U.S. No. 2,280,086.* J. T. Hayward. Iss. 4/21/42. App. 2/23/38.

*Gas Detection.* A method of determining gas in fluid or drilling mud by measuring the change in electrical resistivity of a sample when subjected to reduced pressure.

*U.S. No. 2,282,590.* W. W. Miller. Iss. 5/12/42. App. 6/27/39. Assign. William Miller Corp.

*Galvanometer.* A multiple galvanometer whose elements have a common magnet, metal coil bobbins for electromagnetic damping, hollow torsion heads and suspension ribbons with their flat sides at right angles.

*U.S. No. 2,282,654.* W. L. Horner. Iss. 5/12/42. App. 1/3/38 and 8/8/40. Assign. Core Laboratories, Inc.

*Apparatus for Determining Fluid Content of Solids.* A sealed heater for distilling off fluids contained in rock samples and a graduated collecting tube for determining their quantity.

*U.S. No. 2,283,180.* J. A. Buchanan, U. S. N. Iss. 5/19/42. App. 1/2/41.

*Accelerometer.* A maximum or minimum type accelerometer of the contact type, using either d-c across the contacts or a distinctive a-c tone.

## CONTRIBUTORS

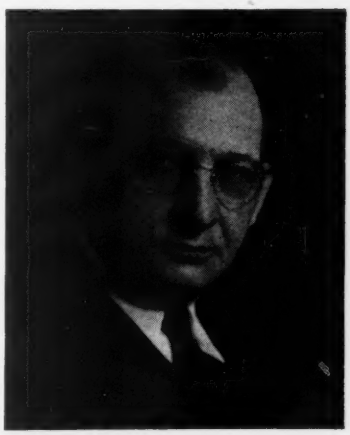
H. B. PEACOCK

H. B. PEACOCK received his A.B. degree in 1921, M.S. in 1922, and Ph.D. in 1925 from the State University of Iowa with major in Physics. During the First World War he served for eighteen months in the Field Artillery Branch of the U. S. Army. After one year as Instructor in Physics at the University of Arizona, he entered the geophysical field with Geophysical Research Corporation in 1926. He has been associated with Geophysical Service, Inc. since its organization in 1930. He is a member of the American Physical Society, American Association for the Advancement of Science, American Association of Petroleum Geologists, the Seismological Society of America, and the Society of Exploration Geophysicists, serving as President of the latter in 1941.

HERBERT HOOVER, JR., received a degree in Mining Engineering in 1925 from Stanford University, and subsequently received his M.B.A. in 1927 from Harvard. Since that time he has done consulting work in communications and exploration, and has been associated with Western Air Express, T.W.A., and the California Institute of Technology. Since 1934 he has been President of the United Geophysical Company and the Consolidated Engineering Corporation. He is a member of the American Institute of Mining and Metallurgical Engineers, the American Association of Petroleum Geologists, the American Institute of Radio Engineers, the Seismological Society of America, the American Association for the Advancement of Science, and the Society of Exploration Geophysicists.

HERBERT HOOVER, JR.

PAUL WEAVER: Former President of the Society of Exploration Geophysicists, and now Vice-President of the American Association of Petroleum Geologists. Was graduated from Columbia University in 1908; worked one year with the Coast & Geodetic Survey on magnetic and seismograph data, and one year with the United States Geological Survey. In 1910 he went to Trinidad as geologist; and in 1911 to Mexico where he was geologist, drilling superintendent, and head of the Exploration Department, and finally technical advisor to the Mexican Eagle Oil Company until 1926. During 1923, he directed the first torsion balance and first seismograph operations in Mexico. Since 1926, he has been with the Gulf Oil Corporation with headquarters in Houston, Texas, where, at present, he is Chief Geophysicist.



PAUL WEAVER

L. L. NETTLETON. See GEOPHYSICS, vol. VI, No. 3, p. 303, (July 1941) for biography and photograph.

JOSEPH A. SHARPE. See GEOPHYSICS, vol. VII, No. 2, p. 208, (April 1942) for biography and photograph.

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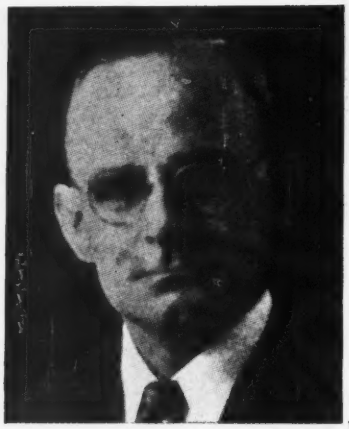

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# THE SOCIETY ROUND TABLE

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The Executive Committee has approved for publication the names of the following candidates for membership in the Society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the Secretary within thirty days. (Names of sponsors are placed beneath the name of each nominee.)

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G. H. Westby, John H. Wilson, Henry C. Cortes

Gilman Alseth Berg
Robert H. Ray, Kenneth E. Burg, J. W. Thomas

Axel Emil Berndes, Jr.
M. E. Hibbler, Roy L. Lay, V. E. Child

James McKean Bugbee
F. Goldstone, Paul Weaver, W. M. Rust, Jr.

Francis Ayers Hale
Walter D. Baird, Phil P. Gaby, Cecil H. Green

Oswald Alphonse Itria
B. D. Lee, Walter S. Olson, Alexander Wolf

Arnold John Frederick Siegert
Alexander Wolf, Laurence G. Cowles, J. F. Gallie

ASSOCIATE

Robert Tyrie Benton
P. P. Conrad, A. E. Mix, C. H. Gerdes

Donald McClure Davis
C. Hewitt Dix, L. W. Saunders, Cecil E. Reel

Will Silva
W. S. Olson, Louis A. Scholl, Jr., Alexander Wolf

STUDENT

Clinton O. Hurd
Dart Wantland, R. Maurice Tripp, W. S. Levings

## THE TWELFTH ANNUAL MEETING OF THE SOCIETY OF EXPLORATION GEOPHYSICISTS, COSMOPOLITAN HOTEL, DENVER, COLORADO, APRIL 22–24, 1942

The Twelfth Annual Meeting of the Society of Exploration Geophysicists was held in Denver, Colorado, at the Cosmopolitan Hotel, April 22–24, 1942, coincidentally with the Annual Conventions of the American Association of Petroleum Geologists and the Society of Economic Paleontologists and Mineralogists. On Wednesday, April 22, and on Thursday morning, April 23, the technical sessions of the three organizations were held in conjunction. On Friday, April 24, the three met separately for the presen-

tation of papers not of joint interest. Abstracts and titles of papers of interest to geophysicists are presented elsewhere in this section, with the exception of those papers which are being published in this issue of GEOPHYSICS.

On Thursday afternoon, despite rainfall which later turned to snow, a scheduled inspection trip was made to the Colorado Museum of Natural History and the Engineering Laboratories of the United States Bureau of Reclamation in Denver, and to the Geological and Geophysical Departments of the Colorado School of Mines in Golden. Various exhibits had been set up in Berthoud Hall at the School of Mines to illustrate the exploration methods now in common use. An informal dinner was subsequently held in Guggenheim Hall, followed by a discussion by Paul Weaver of "The Relative Place of Empirical and Analytical Methods in Geophysical Interpretation."

Arrangements for the inspection trip were made by C. A. Heiland, Dart Wantland, and R. Maurice Tripp. Heiland also served on the Program Committee under the chairmanship of F. Goldstone. Other members of the Program and Arrangements Committee were L. L. Nettleton, A. B. Bryan, Henry Salvatori, J. H. Pernell, and D. S. Hughes.

## MEMBERS REGISTERED AT THE TWELFTH ANNUAL MEETING

L. F. Athy
James A. Ballard
A. J. Barthelmes
A. F. Beck
F. L. Bishop
L. W. Blau
C. Maynard Boos
Frank W. Borman
W. T. Born
Ralph R. Brewer, Jr.
Hart Brown
Montgomery Budd
Kenneth E. Burg
G. W. Carr
E. L. Caster
R. W. Clark
Paul F. Clement
Jack R. Cooper
Henry C. Cortes
W. H. Courtier
Harris Cox
Ira H. Cram
John M. Crawford
N. C. Davies
Donald M. Davis
Alexander Deussen
C. Hewitt Dix
Milton Dobrin
John Doering
Chester J. Donnally
C. H. Dresbach
Robert S. Duty, Jr.
Karl Dyk
C. M. England
L. Y. Faust
R. E. Fearon
Herbert J. Ferber
John L. Ferguson
L. I. Freeman
J. F. Gallie
Derry Gardner
W. B. Gealy
John A. Gillin
Andrew Gilmour
F. Goldstone
H. V. Goss
Cecil H. Green
W. G. Green
T. I. Harkins
Bruce H. Harlton
Sidon Harris
J. E. Hawkins
J. C. Heggblom
C. A. Heiland
W. B. Hogg
Herbert Hoover, Jr.
J. W. Hoover
Frank Ittner
Frank M. Johnston
F. H. Lahee
J. E. LaRue
Joseph LeConte
F. B. Leedy
O. C. Lester, Jr.
W. S. Levings
Dick Martin
L. W. MacNaughton
T. A. Manhart
C. G. McBurney
Downs McCloskey
E. V. McCollum
John McCullagh
Eugene McDermott
R. L. McLaren
Ethel Ward McLemore
James B. Macelwane
James A. Moore
James L. Morris
L. L. Nettleton
L. Murray Neumann
W. W. Newton
F. W. Oudt
J. E. Owen
H. G. Patrick
H. B. Peacock
J. H. Pernell
O. S. Petty

Wallace E. Pratt
W. R. Ransone
Robert H. Ray
F. F. Reynolds
Antonio Garcia Rojas
F. W. Rolshausen
Frederick Romberg
W. M. Rust, Jr.
Henry Salvatori
Edward G. Schempf
Henry Schoellhorn
J. P. Schumacher
O. A. Seager
W. A. Seyffert
Joseph A. Sharpe
E. S. Sherar
T. R. Shugart
D. C. Skeels
Joshua L. Soske
Booth B. Strange
Olaf F. Sundt
B. G. Swan
L. A. Scholl, Jr.
Garvin L. Taylor
W. Harlan Taylor
Norman P. Teague
J. W. Thomas
Frederick A. Tompkins
R. Maurice Tripp
Jess Vernon
Dart Wantland
Kenneth H. Waters
J. S. Watt
B. B. Weatherby
Paul Weaver
Wm. M. Wells
G. H. Westby
M. B. Widess
Stanley W. Wilcox
P. S. Williams
John H. Wilson
B. O. Winkler
R.D. Wyckoff

## MINUTES OF THE ANNUAL BUSINESS MEETING OF THE SOCIETY OF EXPLORATION GEOPHYSICISTS, HELD IN THE COSMOPOLITAN HOTEL, ROOM D, APRIL 24, 1942

The meeting was called to order by President H. B. Peacock at 9:15 A.M., April 24, 1942, in Room D of the Cosmopolitan Hotel, Denver, Colorado. In the absence of the Secretary-Treasurer, W. M. Rust, Jr., reading of the minutes of the preceding business meeting was dispensed with. Business Manager J. F. Gallie was called upon, however, to present in brief the Annual Report of the Secretary-Treasurer. As of December 31, 1941, the Society showed an increase in assets over the previous year of $2,264.17.

Editor R. D. Wyckoff was then called upon to present a report covering editorial business. He urged the members to give all possible aid to the incoming Editor in the preparation and solicitation of papers for publication in GEOPHYSICS in the coming year, cautioning them that the quality and number of papers would be decreased of necessity without their active support.

President Peacock then announced the results of the balloting, as follows:

President, F. Goldstone
Vice-President, R. D. Wyckoff
Editor, Joseph A. Sharpe
Secretary-Treasurer, T. I. Harkins.

Incoming President Goldstone then announced that $2,000 was to be invested in Government War Bonds on behalf of the Society. Subsequently, B. B. Weatherby, former Society President, read a resolution (for text see April issue) urging the formation of a War Efforts Advisory Committee. A motion was made and passed that such a committee be appointed forthwith.

There being no further business, upon motion being made and passed, the meeting was adjourned.

Respectfully submitted,
W. M. RUST, JR.

## NOTE ON THE BALLOT FOR THE ELECTION OF OFFICERS OF THE SOCIETY OF EXPLORATION GEOPHYSICISTS FOR THE YEAR APRIL, 1942–APRIL, 1943

In the 1942 election of officers, 391 members mailed ballots to the Secretary-Treasurer. Of these 20 had to be discarded because the voting member had not paid his dues at least ten days prior to the Annual Meeting, as required by the Society Constitution, 8 bore no signature, and 2 were received too late for consideration. Attention of members is again called to the provision in the Society Constitution that: "Ballots to be valid must be enclosed in an envelope carrying on the outside the written signature of the member submitting the ballot, and must be received by the Secretary-Treasurer at his officially recognized address not later than ten days prior to the Annual Meeting. Only ballots received from members in good standing as of a date ten days prior to the Annual Meeting shall be valid."

Respectfully submitted,
W. M. RUST, JR., *Secretary-Treasurer*

## AMENDMENTS TO THE BY-LAWS OF THE CONSTITUTION OF THE SOCIETY OF EXPLORATION GEOPHYSICISTS

In accordance with the provisions of Article VI-A-1 of the By-Laws, the following amendments to the By-Laws of the Constitution of the Society of Exploration Geophysicists were voted by the members of the Business Committee in session at the annual meeting held in Denver, Colorado, April 22–24, 1942:

1. Under II-A-Publications, a fourth paragraph to be inserted, as follows:
   4. The Executive Committee may authorize the awarding of suitable prizes for the best papers submitted for publication in GEOPHYSICS under conditions designated by it.
2. Under V-A-1 Business Committee:
   Strike out "The Executive Committee may institute a Business Committee—" and substitute "The Business Committee shall be a standing committee of the Society—."

## TITLES AND ABSTRACTS OF PAPERS

All papers of geophysical interest which were presented at the joint meetings of the S.E.G., A.A.P.G., and S.E.P.M. have been combined in this issue of GEOPHYSICS, with the exception of L. L. Nettleton's *Recent Experimental and Geophysical Evidence on the Mechanics of Salt Dome Formations.* An abstract of this paper, which will appear in a forthcoming issue of the A.A.P.G. BULLETIN, is reprinted below.

L. L. NETTLETON, Gulf Research and Development Company, Pittsburgh, Pennsylvania.

*Recent Experimental and Geophysical Evidence on the Mechanics of Salt Dome Formations.*

In 1934 the present author presented a theory of salt dome formation and illustrated it with a model which indicated: (1) that the motive force causing salt uplift is essentially the gravitational force resulting from the fact that the density of the salt is less than that of the surrounding sediments and (2) that both salt and sediments behave

essentially as highly viscous fluids. The present paper considers the experimental and theoretical work, largely by others, carried out since that time which has a bearing on this fluid mechanical theory.

Hubbert in 1937 derived, from dimensional considerations, the numerical relations between the physical constants of a model and its prototype in nature which should be fulfilled to give true dynamic similarity. Dobrin in 1941 determined physical constants of a fluid salt dome model, applied Hubbert's analysis, and established that the model fulfilled the dimensional criteria. By measurement of flow rates and viscosities in a model, he determined the equivalent viscosity for the sediments arriving at a value which is in reasonable accord with determinations by other means. The experiments by Griggs and the thermodynamic development of the physics of stressed solids by Goranson in recent years have interpreted the physical properties of rock material, in terms of long time stresses. This work has clarified and evaluated certain fundamental properties such as "strength," "plasticity," etc. that are directly applicable to the fluid mechanical postulate of salt dome formation. Finally, recent extensive geophysical work and drilling around salt domes have revealed the frequent existence of rim synclines which are a natural consequence of the fluid mechanical theory and which were relatively unknown or unrecognized as such at the time of the earlier paper. All of this work seems to confirm the general hypothesis that salt dome formation is largely a fluid-mechanical process.

## Papers Presented or Read by Title at the Technical Sessions of the Society of Exploration Geophysicists, Friday, April 24, 1942

1. B. G. Swan, Continental Oil Company, Ponca City, Oklahoma.

*Areal Distribution of Velocities in the Texas Gulf Coast.*

Contoured maps showing areal distribution of velocities at constant time are presented for three areas on the Texas Gulf Coast, namely, League City, Northwest Manvel, and an area extending a considerable distance north from the West Citrus Grove structure. Data were obtained in the regular course of operations, a procedure being followed which allowed velocity computations from reversed spreads of 0 to 4500′ and 0 to 5400′. The basic formula

$$V^2=\frac{x^2-x_1^2}{t^2-t_1^2}$$

was used in the construction of Time-Depth curves for each determination. Comparisons of two of these curves with nearby well survey curves are shown.

From the Time-Depth curves depths at constant times were read and plotted on maps for contouring and correction purposes. Comparison between the regular seismic maps and those corrected for the varying velocity distribution, as well as with the generalized subsurface maps can be made by referring to the various maps presented.

2. L. E. Deacon, Shell Oil Company

*An Analysis of Abnormal Reflexions*

During the course of a reflexion survey of an area in Southwest Texas, a group of seismograms was obtained on which were recorded a number of events having abnormal

apparent velocities. The dips computed from these events on the assumption that they were conventional reflexions in the plane of the profile were much larger than the anticipated stratigraphic dip. This paper presents a discussion of the possible origins of these events and an analysis which affords considerable evidence that they originated on fault planes.

3. C. A. SWARTZ, Gulf Research and Development Company
*Seismograph Evidence Regarding the Depth of the Salt in the Salt Dome Province of Southern Mississippi.*

In the salt dome province of southern Mississippi, wherein numerous shallow piercement type salt domes are present, fairly convincing seismograph evidence has been obtained as to the depth of the mother salt bed. Reflection records shot and recorded directly over several domes show a number of shallow reflections from the sedimentary beds above the dome, followed by a long blank space at the end of which strong reflected events appear. It is assumed that the blank reflection-free space represents travel time in the uniform salt mass, and that the prominent reflection immediately following is from the source bed of salt. Calculations show the base of the salt to be at sub-sea depths of 23,000 to 25,000 feet.

4. J. A. GILLIN, National Geophysical Company.
LORENZ SHOCK, National Geophysical Company.
E. D. ALCOCK, National Geophysical Company.
*An Application of Seismic Surveying to the Location of Bauxite in Arkansas.*

The exploration for bauxite has been greatly stimulated by the increased demand for aluminum. The geology of the formation of bauxite in Arkansas is closely related to the Syenite exposures on the old land surface at the end of Midway time. A refraction seismic survey mapped the attitude of the high velocity formations identified as Syenite or Paleozoic rocks. By combining this map with a map of the Midway from scattered core holes, a map of the old land surface at the end of Midway time was obtained. By interpreting this map, future explorations by core drills can be guided to the most favorable locations.

5. M. B. DOBRIN, Gulf Research and Development Company.
*An Analytical Method of Making Weathering Corrections.*

A method of weathering is described by which intercept times can be rapidly and accurately computed from first arrival times without the plotting of time-distance curves. The velocities are determined by a mechanical procedure, based on least squares theory, which normally requires no exercise of judgment on the part of the computer. The application of the method to actual field set-ups is illustrated by sample calculations.

6. JOSEPH A. SHARPE, Joint Geophysical Laboratory of Stanolind Oil and Gas Company and Western Geophysical Company.
*The Effect of Charge Size on Reflection Records.*

The writer has collected a large number of recordings, made under carefully controlled conditions, in which the size of charge has been changed by a factor of 5:1 or 10:1. Sample recordings will be exhibited which illustrate the effect of charge size on the ratio of reflected energy to ground roll and other non-reflection interference, and the effect of charge size on the frequency content of reflected motion.

7. KENNETH H. WATERS, National Geophysical Company.
R. D. ARNETT, National Geophysical Company.
*Aspects of Seismic Curved Path Computations.*

Based on measured velocity data from a South Arkansas well, curved rays normal to the reflecting horizons at the point of incidence are determined using curved path formulae for subsurface formations with inclinations of varying magnitudes. These data are compared with "straight line" data derived by using several velocity stratification assumptions. Curved path data concerning the position of the reflecting point and the angle of inclination are seen to agree closely with data obtained using certain "straight line" paths.

8. C. HEWITT DIX, United Geophysical Company.
*Dip Computations Below Unconformities.*

It is often found that an unconformity separates sections of appreciable velocity difference. In such cases the computation of dips of reflectors below the unconformity will generally be influenced by the dip of the unconformity interface. The present note shows how this computation can be carried through and illustrates the effects involved in a particular case.

9. E. E. ROSAIRE, Subterrex, Houston, Texas.
L. HORVITZ, Subterrex, Houston, Texas.
*The Sedimentary Hydrocarbon Survey of the Washburn Ranch Oil Field, La Salle County, Texas.*

Data obtained during a sedimentary hydrocarbon survey of the Washburn Ranch oil field in La Salle County, Texas, are presented showing the anomaly mapped in this area.

10. E. V. MCCOLLUM, Mott-Smith Corporation, Houston, Texas.
*Gravity Expression of the Hatchetigbee Anticline.*

Gravity data are presented showing there to be a local minimum of gravity over the Hatchetigbee anticline leading to the conclusion that associated with this feature there is probably a very substantial thickening in the salt section.

11. D. C. SKEELS, Standard Oil Company of New Jersey, 30 Rockefeller Plaza, New York City.
*The Value of Quantitative Interpretation of Gravity Data.*

Although there is no unique interpretation of a given set of gravity data, there are many cases in which quantitative interpretation is decidedly worthwhile. This is especially true in cases where the gravity data are supplemented by a certain amount of geological data, or where the gravity anomaly is of such a shape that the range of possible solutions can be rather closely limited. Three examples are given of interpretations of actual data.

12. L. L. NETTLETON, Gulf Research and Development Company, Pittsburgh, Pennsylvania.
*Magnetic and Gravity Calculations.*

Formulas and curves are given for calculating gravity and magnetic effects for various geometric forms. For the most part these are not new, but they are assembled into convenient form with a convenient set of master curves. The units and constants

are chosen to facilitate rapid calculations to test possible causes of observed gravity and magnetic anomalies. For certain bodies, use is made of the principle of considering the matter as condensed onto a thin sheet, which results in great simplification of the formulas without important loss of precision for most geophysical purposes. This principle does not seem to have received the attention which it deserves in connection with geophysical calculations. The application of solid angles to gravity and magnetic calculations, together with a chart of solid angles are included. Finally, there is given an example of the application of some of the methods presented. In view of the inherent ambiguities in the various mass or magnetic distributions which can account for a given gravity or magnetic anomaly, the approximate methods given should serve for all necessary calculations in connection with the interpretation of any but quite detailed surveys where control in addition to the magnetic or gravity data is available.

13. A. J. F. SIEGERT, The Texas Company, Houston, Texas.
*An Instrument for the Computation of Gravity Anomalies.*

A mechanical device has been designed to evaluate the gravity anomaly caused by an arbitrarily given finite body. It can be used as an aid in gravity and magnetic interpretation work and for the computation of terrain corrections in gravity work.

14. VIRGIL BARNES, Bureau of Economic Geology, Austin, Texas.
FREDERICK ROMBERG, LaCoste and Romberg, Austin, Texas.
*Gravitational and Magnetic Anomalies Over a Body of Magnetite.*

This paper gives the results of gravimetric and magnetic surveys over Iron Mountain, a magnetite body in Llano County, Texas. The observed anomalies are compared with the known extent of the ore. This comparison suggests that there is more ore than was supposed, and this possibility is examined quantitatively.

15. C. A. HEILAND, Colorado School of Mines, Golden, Colorado.
*A Rapid Method for Measuring the Profile Components of Horizontal and Vertical Gravity Gradients.*

The trend in gravity exploration in the past years indicates the rather remarkable fact that a method of low resolving power (the gravity meter) has replaced one of a higher resolving power (the torsion balance). This is entirely due to the superior speed of the former and suggests an instrument and procedure in which observation time is reduced by (1) reduction in number of quantities measured; (2) use of a reference direction near that of the maximum effect; (3) elimination of the torsionless position as unknown; (4) reduction in period, with compensating increase in optical sensitivity; (5) stabilization of thermal conditions. These objectives are attained by (1) measuring the profile components of gradients and curvature values, preferably at right angles to the assumed strike; whereby, for an ideal two-dimensional feature, also the vertical gravity gradient is obtained, and the vertical and horizontal gravity components may be calculated by integration; (2) by holding the torsionless position constant with temperature control; (3) by decreasing the period and observation time to 3–4 minutes, and (4) by using a beam arrangement which will give the gradient in only one azimuth, and the profile gradient of the horizontal gravity component in a second azimuth if desired. Latitude and terrain corrections are also somewhat simplified by the proposed procedure.

16. DART WANTLAND, Colorado School of Mines, Golden, Colorado.
*Magnetic Interpretation.*

The quantities measured in magnetic prospecting are considered, and a classification of magnetic anomalies is presented. Pole depth calculations and their limitations, the shift of magnetic and structural axes, and other relationships between subsurface geologic conditions and magnetic anomalies are discussed. The usefulness of magnetic work in an exploration program and the idea of magnetic stratigraphic changes and their significance in interpretation are treated.

17. C. M. ENGLAND, Geophysical Research Corporation, Tulsa, Oklahoma.
*A Resistivity Survey of the Monument Oil Field.*

This paper describes an electrical resistivity survey made in 1935 of an area in New Mexico now known as the Monument Field. From the data obtained a map showing the structure at the base of the Red Beds was prepared which is in good agreement with structure disclosed by wells later drilled.

18. DANIEL SILVERMAN, Joint Geophysical Laboratory of the Stanolind Oil and Gas Company and Western Geophysical Company, Tulsa, Oklahoma.
DAVID SHEFFET, Naval Ordnance Laboratory, Washington, D. C.
*Note on the Transmission of Radio Waves Through the Earth.*

Experiments are described and data reported on the attenuation suffered by radio signals in passing through shallow layers of earth. Comparison is made between the measured attentuations and values computed from published formulae.

19. ALFRED WOLF, Geophysical Research Corporation, Tulsa, Oklahoma.
*The Impedance of a Grounded Wire.*

The impedance of an insulated wire stretched along the surface of the earth, regarded as a homogeneous conductor, is a function of frequency and of the conductivity of the earth. Formulas are given for the inductance and the resistance of such a wire which are applicable under conditions met with in geophysical prospecting.

20. THOMAS S. WEST, Three Rivers, Texas.
CLARENCE C. BEACHAM, Three Rivers, Texas.
*Precise Measurement of the Electrical Resistivity Anomaly Resulting from Oil or Gas Saturation.*

A precise determination of deep electrical resistivity anomalies is obtained by a method of accurately correcting direct current electrical resistivity data for the influence of shallow inhomogeneities. This procedure, when employed with precise measurement of current and potential difference in areas of identical subsurface conditions, permits the obtaining of curves indicating the rate of variation of apparent resistivity with electrode separation which may be duplicated as to form to within one fourth of one per cent. Methods are described of determining under field conditions, the depth of prospecting, the location of the subsurface area prospected, and the fact that curves are independent of shallow inhomogeneities.

Correction for shallow inhomogeneities results in curves indicating the variation of apparent resistivity with electrode separation (i.e., depth) which have relatively minute but persistent features. Such curves may be correlated over considerable areas. De-

tailed surveys of the Sam Fordyce, Oakville, and Seven Sisters fields as well as other areas in Southwest Texas are shown.

Features on curves are believed to be of electro-chemical origin rather than a result of variation of ohmic resistivity. This conclusion is supported by the fact that the largest and sharpest features are obtained in areas in which subsurface beds are practically homogeneous as to resistivity as measured by electrical well logging devices. Features also appear to increase in magnitude as current density is decreased.

21. J. H. JONES, Anglo-Iranian Oil Company, London, England.
*A Proposed Method of Measuring the Derivatives of the Earth's Magnetic Field.*

The method of measuring the derivatives of the Earth's magnetic field which is proposed depends on the fact that a small steady magnetic field will modify the e.m.f. induced in the secondary coil of a detector with a core of magnetizable material possessing high initial permeability coefficient and a high rate of increase of this coefficient with the strength of the magnetizing field. It is shown that a detector of this type is equivalent to an inductor coil rotating with angular speed equal to the periodicity of the alternating magnetizing field.

22. H. M. EVJEN, Elflex Company, Houston, Texas.
*Utility of Electrical Methods in Geophysical Exploration.*

## ANNUAL REPORT OF THE SECRETARY-TREASURER OF THE SOCIETY OF EXPLORATION GEOPHYSICISTS

The increase in membership in the Society of Exploration Geophysicists is indicated in the following figures, compiled as of December 31, 1941:

| *Year* | *Honorary* | *Active* | *Associate* | *Student* | *Total* | *Increase* |
|---|---|---|---|---|---|---|
| 1930 | 0 | 34 | 5 | 0 | 39 | |
| 1931 | 2 | 68 | 11 | 0 | 81 | 42 |
| 1932 | 2 | 83 | 11 | 0 | 96 | 15 |
| 1933 | 2 | 91 | 10 | 0 | 103 | 7 |
| 1934 | 2 | 141 | 23 | 0 | 166 | 63 |
| 1935 | 2 | 156 | 31 | 0 | 189 | 23 |
| 1936 | 4 | 195 | 34 | 0 | 233 | 44 |
| 1937 | 4 | 367 | 112 | 0 | 483 | 250 |
| 1938 | 4 | 510 | 158 | 0 | 672 | 189 |
| 1939 | 4 | 632 | 185 | 0 | 821 | 149 |
| 1940 | 4 | 700 | 188 | 0 | 892 | 71 |
| 1941 | 4 | 728 | 168 | 7 | 907 | 15 |

The financial condition of the Society of Exploration Geophysicists, as of December 31, 1941, is indicated in the following report, reproduced from the annual audit. This is exclusive of approximately 7,000 copies of past publications, with a minimum value, at $1 each (the cost to members), of $7,000.

BALANCE SHEET—DECEMBER 31, 1941

*Current* ASSETS

| | | | |
|---|---|---|---|
| *Cash* | | | |
| In Banks | | $ 8,464.03 | |
| *Accounts Receivable* | | | |
| Advertising | $441.31 | | |
| Membership Dues | 392.00 | | |
| Reprints | 171.39 | | |
| Back Numbers | 22.00 | 1,026.70 | $ 9,490.73 |
| *Investment* | | | |
| Farm and Home Savings and Loan Association Full Paid Shares Certificate | | | 5,000.00 |
| *Office Equipment* | | | |
| Cost | | $ 89.95 | |
| Less: Allowance for Depreciation | | 13.95 | 76.00 |
| | | | $14,566.73 |

*Current* LIABILITIES

| | | |
|---|---|---|
| *Accounts Payable* | | |
| For Expenses, etc | | $ 1,699.43 |
| *Deferred Income* | | |
| Prepaid Dues and Subscriptions | | 272.56 |
| *Surplus* | | |
| Balance January 1, 1941 | $10,330.57 | |
| *Add* | | |
| Increase from Current Year Operations—Per Statement of Income and Expense | 2,264.17 | 12,594.74 |
| | | $14,566.73 |

## INCOME AND EXPENSE—DECEMBER 31, 1941

| | | | | |
|---|---|---|---|---|
| **INCOME** | | | | |
| *Membership Dues* | | $4,462.50 | | |
| *Publications* | | | | |
| Advertising | $2,624.35 | | | |
| Subscriptions | 1,247.63 | | | |
| Back Numbers | 632.90 | | | |
| Reprints | 314.56 | 4,819.44 | | |
| *Other Income* | | | | |
| Interest Received | $ 64.74 | | | |
| Commissions on Publications | 27.60 | | | |
| Credit Balances Written Off | 21.78 | 114.12 | $9,396.06 | |
| *Less: Discounts to Colleges, etc. on Subscriptions and Back Numbers* | | | 147.00 | $9,249.06 |
| *Publication Costs* | **COSTS AND EXPENSES** | | | |
| GEOPHYSICS: | | | | |
| Vol. VI—No. 1—132 Pages | | $ 766.14 | | |
| No. 2—134 Pages | | 833.19 | | |
| No. 3—128 Pages | | 797.38 | | |
| No. 4—204 Pages | | 1,164.67 | $3,561.38 | |
| Reprints | | | 274.26 | $3,835.64 |
| *Expenses* | | | | |
| Salary—Business Manager | | $1,200.00 | | |
| Commissions: | | | | |
| Advertising: | | | | |
| Business Manager | $ 281.09 | | | |
| Agencies | 315.39 | | | |
| Subscriptions, etc.—Agencies | 52.10 | 648.58 | | |
| Bad Debts | | 354.56 | | |
| Annual Meeting Expense: | | | | |
| Programs, Circulars and Registration Cards | $ 178.65 | | | |
| Prorata A.A.P.G. | 69.00 | | | |
| Traveling Expense—Bus. Mgr. | 56.55 | | | |
| Signs, Badges, etc. | 39.93 | | | |
| Stenographers | 30.00 | | | |
| Luncheon—Net | 24.20 | | | |
| Telephone and Telegraph | 18.12 | | | |
| | $ 416.45 | | | |
| Less: Paid by A.A.P.G. | 300.00 | 116.45 | | |
| Stationery and Office Supplies | | 291.26 | | |
| Postage and P. O. Box | | 231.02 | | |
| Auditing | | 105.73 | | |
| Telephone and Telegraph | | 86.73 | | |
| Binding, etc. | | 40.66 | | |
| Express and Freight | | 34.17 | | |
| Bond Premiums | | 17.50 | | |
| Society Card—A.A.P.G. | | 15.00 | | |
| Depreciation | | 6.15 | | |
| Bank Charges | | 1.44 | 3,149.25 | 6,984.89 |
| *Excess of Income Over Costs and Expenses* | | | | $2,264.17 |

Respectfully submitted,
W. M. RUST, JR., *Secretary-Treasurer*

## PERSONAL ITEMS

JOSEPH G. HATHEWAY has returned to the States from Venezuela, where he was employed by the Schlumberger Well Surveying Corporation, and is awaiting induction into the U. S. Army at his home, 3427 West 33rd Avenue, Denver, Colorado.

H. WAYNE HOYLMAN, of the Gulf Research and Development Co., has returned to Pittsburgh, Pennsylvania, from Puerto Cabezas, Nicaragua.

SAM ZIMERMAN, Party Chief with the Carter Oil Co., has been transferred from Hope, Arkansas, to Box 87, Jonesville, Louisiana.

J. C. POLLARD has resigned his position as Assistant Director of Geophysics of the Magnolia Petroleum Co., effective May 25, 1942. He will hereafter be associated with Robert H. Ray, Inc., and Rogers-Ray, Inc., in geophysical contracting and consulting work, with headquarters in the Gulf Building, Houston, Texas.

PAUL E. NASH, who has been with the Geological and Geophysical Department of Vacuum and Magnolia since 1926, became Assistant Director of Geophysics of the Magnolia Petroleum Co., effective May 25, 1942.

LT. E. F. MCMULLIN is now stationed in Oklahoma City, with the mailing address 2324 NE 25th.

B. M. MEADOR, formerly with the International Petroleum Co. in Guayaquil, Ecuador, has accepted a position in the Aircraft Radio Laboratory of the Signal Corps. He may be addressed at 520 W. Fairview Avenue, Dayton, Ohio.

MARVIN ROMBERG has returned safely from Sumatra and may be addressed c/o Carter Oil Company, National Bank Building, Tulsa, Oklahoma.

CHARLES A. SHAPARD, formerly with the Independent Exploration Company, is serving as a Ballistic Engineer with E. I. du Pont de Nemours & Co., in the Alabama Ordnance Works. Mail will reach him c/o General Delivery, Childersburg, Alabama.

CAPTAIN JOHN V. LONG should be addressed at 4120 5th Avenue, San Diego, California.

E. D. WILLIAMS, President of the Universal Exploration Co., announces that JOHN P. MEAD, formerly with the Superior Oil Co. of California, has joined his staff as Vice-President and Supervisor.

O. B. MANES, Party Chief with the Stanolind Oil and Gas Co., should be addressed at P. O. Box 135, Natchitoches, Louisiana.

S. A. MARTIN, JR., formerly with the Humble Oil and Refining Company, is now employed in the Radiation Laboratory of the Massachusetts Institute of Technology, Cambridge, Massachusetts.

H. W. STRALEY, III, head of the department of geology at Baylor University, has resigned to enter the employ of the Eastern Exploration Company. He will be in the Interior and Appalachian Fields, and his temporary address will be Princeton, West Virginia.

WALTER D. BAIRD, Party Chief with Geophysical Service, Inc., moved from Fresno to P. O. Box 1528, Stockton, California, May 15th.

ROBERT L. AUGENTHALER, formerly with the California Co. in Merced, California, is now with the Standard Oil Co. of British Columbia, Ltd., 700 Lancaster Building, Calgary, Alberta, Canada.

L. F. FISCHER has left the Gulf Oil Co. to accept employment with the General Geophysical Co. He is now located in Buffalo, Texas.

ALFRED E. STORM, of Geophysical Service, Inc., recently returned safely to the States from the Netherlands East Indies. He is now located in Cardston, Alberta, Canada, but may be addressed at 1311 Republic Bank Building, Dallas, Texas.

BEN S. MELTON is now located at 8621 Georgia Avenue, Silver Spring, Maryland.

R. H. TALLMAN, formerly with the Standard Oil Co. of Egypt in Cairo, is now in Guayaquil, Ecuador, with the mailing address Box 803, after a short stay in the States with the Carter Oil Co.

EDWARD LIPSON advises the Society that he has been commissioned a Major in the Signal Corps of the U. S. Army, with orders to report in Washington June 1. Mail will be forwarded for the present from 1111 Eagle, Houston, Texas.

FRANCIS H. CADY, Computer with the Carter Oil Co., has been transferred from Norman to P. O. Box 170, Sulphur, Oklahoma.

DALE H. MOOSE, Computer with the United Geophysical Co., has been transferred from Marshall, Texas, to P. O. Box 270, Stillwater, Oklahoma.

BERNARD G. HUBNER, JR., Party Chief with the National Geophysical Co., has moved from Stamps, Arkansas, to Texarkana, with the postal address Box 1132.

H. H. EVINGER, formerly with the Gulf Research and Development Company, is serving as a physicist in the Naval Ordnance Laboratory, Navy Yard, Washington, D. C.

W. L. IRBY is another member who has returned safely from the Netherlands East Indies. He may be addressed at the Carter Laboratory, Carter Oil Co., Tulsa, Oklahoma.

J. P. CARSON is now located at P. O. Box 109, Diablo Heights, Canal Zone.

J. M. KILBORN, Magnetometer Party Manager with the Gulf Research and Development Co., has moved from Lubbock to Box 837, Ft. Stockton, Texas.

H. R. MOORMAN has entered foreign work as Chief Geophysicist for Socony-Vacuum Oil Co. C. A., Apartado 246, Caracas, Venezuela.

MAURICE SKLAR, with the Shell Oil Co., Inc., has been transferred from Pearsall to 107 N. Railroad, Groesbeck, Texas.

ERIK THOMSEN should be addressed c/o Stanolind Oil and Gas Co., P. O. Box 591, Tulsa, Oklahoma.